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Quiet Clean Short-Haul Experimental Engine (QCSEE)

Clean Combustor Test Report

by

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16. Abstract

As part of the QCSEE Program, a component pressure test was conducted on a F101 PFRT combustor to evaluate the emissions levels of this combustor design at selected UTW and OTW operating conditions for the QCSEE engine. In addition, two emissions reduction techniques were evaluated which included compressor discharge bleed and sector burning in the combustor.

The results of this test were utilized to compare the expected QCSEE engine emissions levels with the emission goals of the QCSEE Engine Program, which are similar to 1979 EPA Standards for CO, C_xH_y, NO_x and smoke.

Based on these test results, the QCSEE engines will not meet the CO, C_xH_y or smoke requirements (UTW only) even when applying the emissions reduction techniques investigated in this test. Both the UTW and OTW engine were below the QCSEE goals for NO_x.

In order to meet the CO and C_xH_y pollution goals, additional work is under consideration to develop a new Double-Annular Dome combustor for QCSEE based on technology from the NASA-GE Clean Combustor Program.

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SECTION I

SUMMARY

A component pressure test was conducted on a F101 PFRT full-annular combustion system, similar to the QCSEE combustion system, to evaluate the performance and measure the emissions levels at various design and off-design operating conditions for the QCSEE UTW and OTW engines.

Emissions levels of carbon monoxide (CO), hydrocarbons (C_xH_y), oxides of nitrogen (NO_x) and smoke were measured at standard day operating conditions varying from idle to sea level takeoff. Idle emissions reduction techniques including ten-cup sector burning and simulated compressor discharge bleed were evaluated.

The measured gaseous emissions of the F101 PFRT combustor, when tested at the QCSEE UTW and OTW engine operating conditions, compared favorably with emissions data from other component tests of this combustor. However, the results of this component test indicate the current F101 PFRT combustor, when operated at the QCSEE engine cycle conditions, will result in CO, C_xH_y and smoke (UTW only) emissions levels which exceed the applicable 1979 EPA Standards even with the incorporation of sector burning and/or CDP bleed air extraction. The NO_x emissions levels will satisfy the EPA Standards for both the UTW and OTW engine applications.

In order to meet the C_xH_y and CO pollution goals, additional work is under consideration to develop a new Double-Annular Dome Combustor for QCSEE. This combustor design would be derived from the best NASA Double-Annular Dome CF6-50 combustor design which is being evolved in the NASA/GE Clean Combustor Program.

SECTION II

INTRODUCTION

General Electric is currently engaged in the Quiet, Clean, Short-Haul Experimental Engine (QCSEE) Program under Contract NAS3-18021 to NASA-Lewis Research Center. The goals of the QCSEE Program are to demonstrate with the UTW and OTW engines emissions levels consistent with the Environmental Protection Agency (EPA) defined emissions standards, which become effective January 1, 1979 for Class T2-rated thrust of 35,580 N (8,000 lbs) or greater - aircraft turbine engines. These standards set maximum limits on the quantities of C_xH_y, CO, and NO_x, and smoke emissions that can be discharged by engines.

The Class T2 engine standards in the three categories of gaseous emissions are shown in Table I. The standards are defined in terms of pounds of emission per 1000-pound thrust-hours for a prescribed takeoff/landing mission cycle. This prescribed cycle is shown in Table II. The intent of these standards is to limit the quantities of these exhaust constituents that can be discharged within and around airports.

The smoke standards are expressed in terms of the SAE ARP 1179 Smoke Number. The maximum allowable smoke number is dependent on rated engine thrust. For the OTW engine, the smoke number standard is 22 and for the UTW engine the smoke number standard is 24.

An extensive component test was conducted as part of the QCSEE combustor development program. This test was conducted on a F101 PFRT full-annular combustion system, which is similar to the QCSEE system, to evaluate the performance and measure the emission levels at various operating conditions for the QCSEE UTW and OTW engines. The operating conditions selected include the operating modes required in the EPA Standards. In addition, two approaches expected to provide significant reductions in idle emissions, CDP bleed and sector burning, were evaluated. Emissions measurements were obtained through fixed multielement gas sample rakes and analyzed using the on-line gas analysis system (CAROL).

This report presents the description of the combustor, test configuration, test facility, test vehicle, and the data acquisition and reduction methods. The test results are presented in the form of plots of emissions indices and combustor performance parameters. Comparison of the emissions data to the applicable EPA Standards are presented in tabular form which includes all of the specified engine operating parameters and pertinent emissions data at these operating conditions.

Table I. EPA Gaseous Emissions Standards for Class T2 Engines.

<u>Gaseous Emissions</u> (C_xH_y, CO, and NO_x)

- Earliest effective date - January 1, 1979
- Firm standards for engines newly manufactured on or after 1/1/79:

C_xH_y	0.8	EPA Index expressed as: pounds emissions per 1000-pound thrust-hours, for a prescribed cycle.
CO	4.3	
NO_x	3.0	

Table II. EPA Gaseous Emissions Standards, Turbojets and Turbofans.

- Prescribed cycle for Class T2 engines:

Mode	% Power	Time, Minutes
Taxi-idle	Ground idle	19.0
Takeoff	100	0.7
Climbout	85	2.2
Approach	30	4.0
Taxi-idle	Ground idle	7.0

SECTION III

DESCRIPTION OF COMBUSTOR

The F101 PFRT engine combustor was used in this full-annular component emissions test. A cross section of this combustor design is presented in Figure 1.

The PFRT combustor is an advaned, short-length configuration which features the use of a unique airblast-type fuel introduction and atomization design approach. In this combustor design, the dome comprises 20 carbureting swirl cups. Fuel is supplied to each of these swirl cups at low pressure by means of a simple, open-end fuel delivery tube. The carbureting swirl cups have three stages through which air is introduced and mixed with the fuel. In the first stage, the fuel is premixed in a scroll device with a small amount of the combustor airflow, upstream of the flow areas that meter the airflow into the primary combustion zone (dome) of the combustor. Additional airflow is introduced through the primary air swirler which further energizes the fuel/air mixture and carries it to the primary cup exit. At this point, the secondary air swirler introduces air which rotates in a direction opposite to that of air from the primary swirler. Fuel leaving the downstream edge of the primary cup venturi enters the shear region created by the mixing boundaries of the counterrotating flows, and the high aerodynamic shear stress imposed on the fuel produces very fine atomization and highly effective fuel/air mixing over wide ranges of combustor operating conditions. With these excellent atomization and mixing capabilities, very short-length combustor designs are possible. Accordingly, the PFRT combustor is a compact design with very short length compared to other current technology turbofan engine combustors.

Extensive development testing of the PFRT combustor design has been conducted to perfect its operating characteristics. Excellent performance, including low exit temperature pattern and profile factors and acceptable altitude-relight capabilities have been demonstrated in these tests. To date, the PFRT combustor has been used in several General Electric engines. Engine tests have been conducted with this combustor including both ground and flight test evaluations. These engine tests, along with extensive component development testing of this combustor design, have been conducted to optimize its operating characteristics.

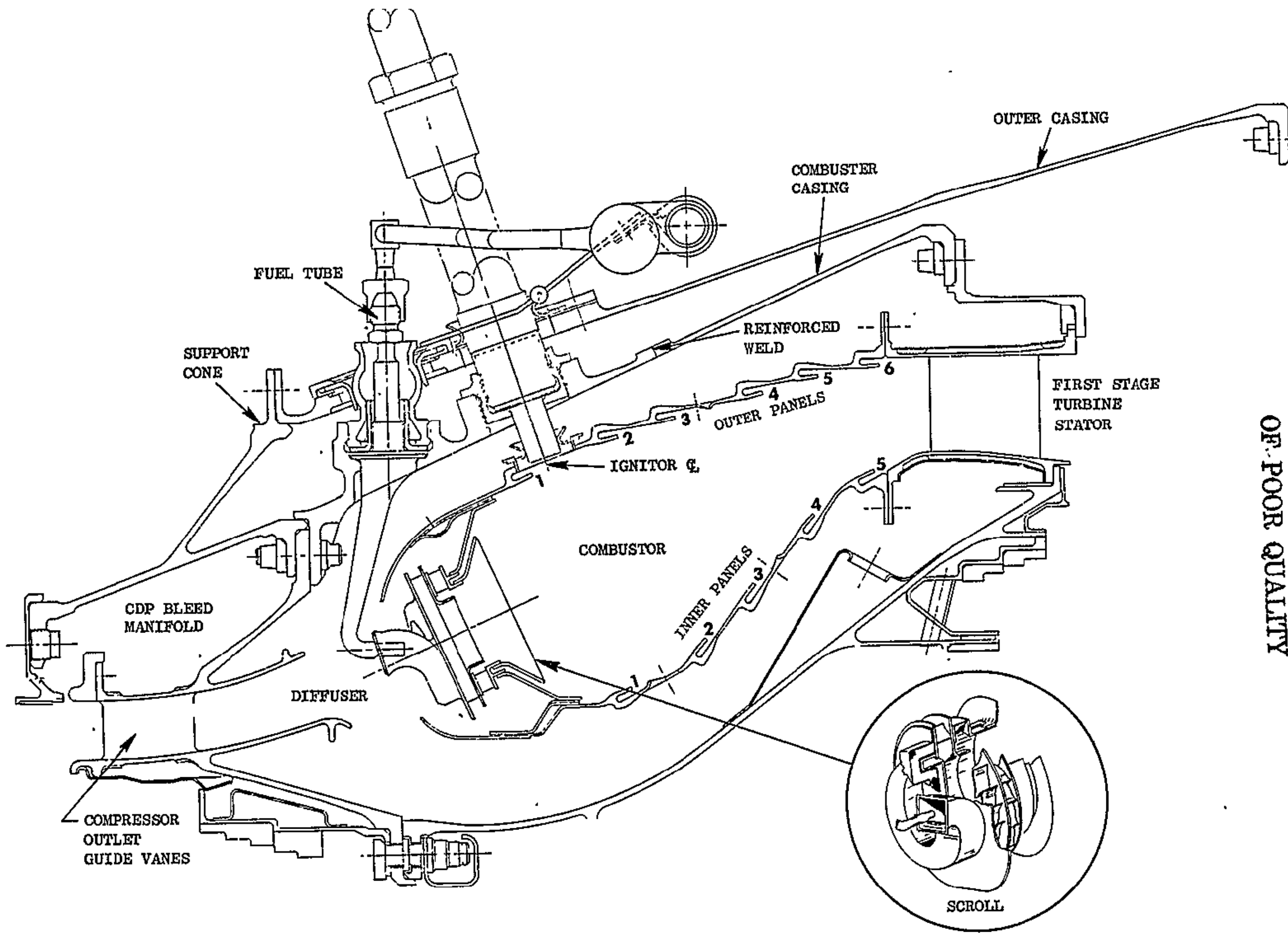


Figure 1. PFRT Combustor Cross Section.

SECTION IV

TEST FACILITY

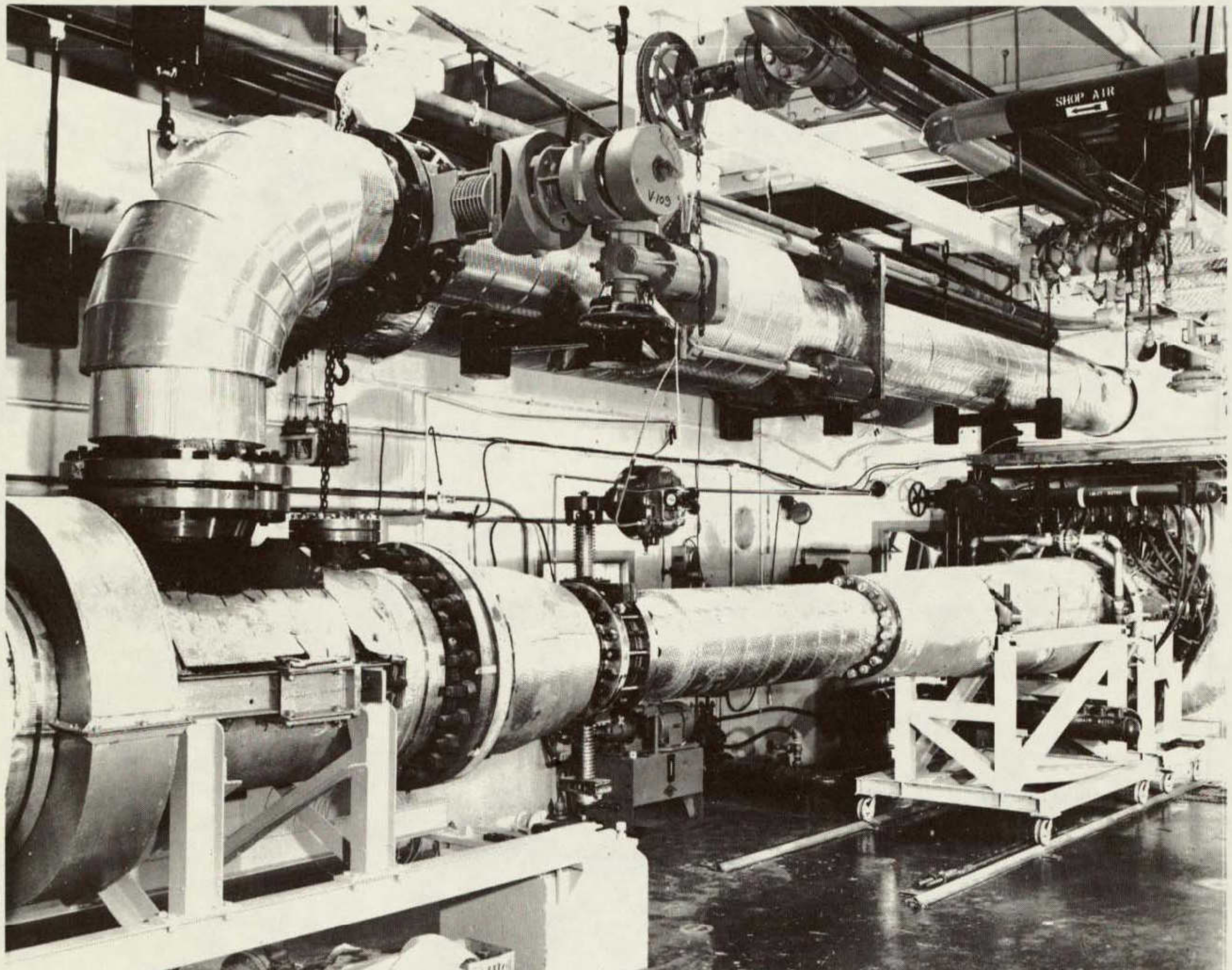
The QCSEE combustor component test evaluations were performed in Test Cell A3, which is located in the General Electric Evendale Plant. This facility is fully equipped with the necessary inlet ducting, exhaust ducting, controls and instrumentation required for conducting full-scale combustor component tests over wide ranges of operating conditions. A view of the interior of the cell is shown in Figure 2. The cell itself is a rectangular chamber with reinforced concrete blast walls on three sides and a lightweight roof. The installed ventilation and safety equipment are designed specifically for tests involving combustible fluids. This cell contains the necessary air piping to accommodate two test vehicles.

In operating this test cell, its utilization is maximized by mounting the test rigs on portable dollies with quick-change connections so that build-up operations are accomplished in another area and the resulting test vehicle occupies the cell only for the duration of its actual testing. This cell operational concept allows the installation of a typical test vehicle in about four hours. The turnaround time from the completion of a test with one vehicle to the start of a test with another is, therefore, only about eight hours. The instrumentation reliability is improved since the sensors are prewired to multiple quick-connect panels and checked out in the favorable environment of the vehicle build-up area.

The control consoles and data recording equipment are located in the adjacent control room. This room is insulated to muffle test noise and facilitate communication and is environmentally controlled for the benefit of the electronic equipment.

Air is supplied to this test cell from a central air supply system. This system has a nominal capacity of 45 kg/sec of continuing airflow at a delivery pressure of up to 2 MN/m^2 (20 atm). The system may also be used for exhaust suction to simulate a pressure altitude up to 8.9 km, with flow rates reduced in proportion to density.

Auxiliary equipment in the air distribution network provides for further conditioning of the delivered air, when required. This conditioning includes 10-micron filtration, drying to a 233° K dewpoint and temperature control. Cold air, down to 217° K, can be provided by piping connections to a turbo-refrigeration unit. Warm air, up to 450° K, can be supplied directly by bypassing the aftercooler. Further heating, up to 922° K, is accomplished with a gas-fired heat exchanger. The gas-fired indirect air heater is designed to accept 36 kg/sec of air from the central air supply system at 450° K and 0.96 MN/m^2 (9.5 atm) pressure and to discharge the air unvitiated at 933° K and 0.84 MN/m^2 (8.3 atm). The heater is capable of accommodating higher flows and higher pressures at reduced outlet temperatures. The heater is a refractory-lined shell 8.2 m in diameter and 13.7 m tall, containing a conical radiating furnace baffle and a heat exchanger.



Combustor
Test Rig

Figure 2. Interior View of Test Cell A3.

Combustors being tested in this cell can be exhausted directly to the atmosphere or can be connected to the facility exhaust system for pressure control. When connected to the facility exhaust system, the combustor pressure can be regulated from the upper limit, imposed by the pressure or flow capacity of the air supply system, down to about 20 kN/m^2 (0.2 atm). Exhaust suction is provided either by the centrifugal compressors of the air supply system or by a two-stage steam ejector system with an interstage condenser.

Liquid fuels are supplied to Cell A3 from two large above-ground tanks, each having a capacity of 114 cubic meters. Each tank is provided with a centrifugal pump to transfer the fuels through 10.2-cm pipelines. The high pressure fuel pumps, located in Cell A3, boost the fuel pressure as high as 826 MN/m^2. The available fuel pressures and flows with these pumps were more than adequate for this test program, with ample margin for metering and control.

SECTION V

TEST VEHICLE AND HARDWARE

The QCSEE combustor evaluations were conducted with an existing F101 full-annular combustor test rig. This full-annular combustor test rig exactly duplicates the aerodynamic combustor flowpath and envelope dimensions of the F101 engine. The test rig consists of an inlet plenum chamber, an inlet diffuser section and a housing for the combustor. Included as a part of this rig is an exit plane fixed rake assembly for obtaining measurements of combustor outlet temperatures and pressures and for extracting gas samples.

Photographs of the test rig are presented in Figure 3. The combustor test rig is basically a cylindrical pressure vessel designed for high-temperature service and fitted with inlet and exit flanges. The rig is equipped with ports and bosses to accommodate fuel nozzles/injectors, igniters and boroscope inspection devices. These ports are located exactly as in the engine design. The rig is also equipped with provisions to extract both turbine cooling air and customer bleed air. These provisions also duplicate those in the engine.

The air inlet connection of the test rig consists of an 81.3-cm diameter pipe flange of special design which is bolted to the air supply plenum of the test cell. In the supply plenum, the flow is mixed and then straightened by grates and screens. Within the test rig, a bullet-nosed centerbody directs the entering airflow into an annular passage. This annular passage simulates the compressor discharge passage of the engine. The inner and outer walls are formed to the contour of the engine's diffuser and the gap is spanned by streamlined outlet guide vanes, similar to those in the engine. Aft of the step diffuser, the centerbody forms the inner wall of the combustor housing. The outer wall is provided with ten 1.1 cm diameter bleed ports, through which a portion of the airflow can be extracted as turbine bleed air. Additional ports are provided on the inner wall to simulate turbine rotor cooling air extraction. The air extracted from these sets of ports is routed through 2-2.1 cm pipes, forward through the centerbody nose, then radially out of the rig.

The combustor test rig is equipped with 20 fuel injector ports, spaced 18° apart. The fuel injectors used in this program were all installed through these existing ports. The fuel was supplied to these injectors through a fuel manifold assembly consisting of four valve segments identical to the F101 fuel manifold assembly. A ball shutoff valve was installed at the fuel manifold inlet to prohibit fuel from entering one-half (ten injectors) of the manifold assembly to demonstrate ten-cup sector burning.

The exhaust end of this combustor test rig is provided with a large diameter flange to which an instrumentation spool section can be joined. The instrumentation spool section used in this program consisted of an existing short-flanged pipe with a ring incorporating mounting pads for gas sampling rakes at specific circumferential locations. In the array used in the program, ten gas sampling rakes and one total pressure rake were mounted in

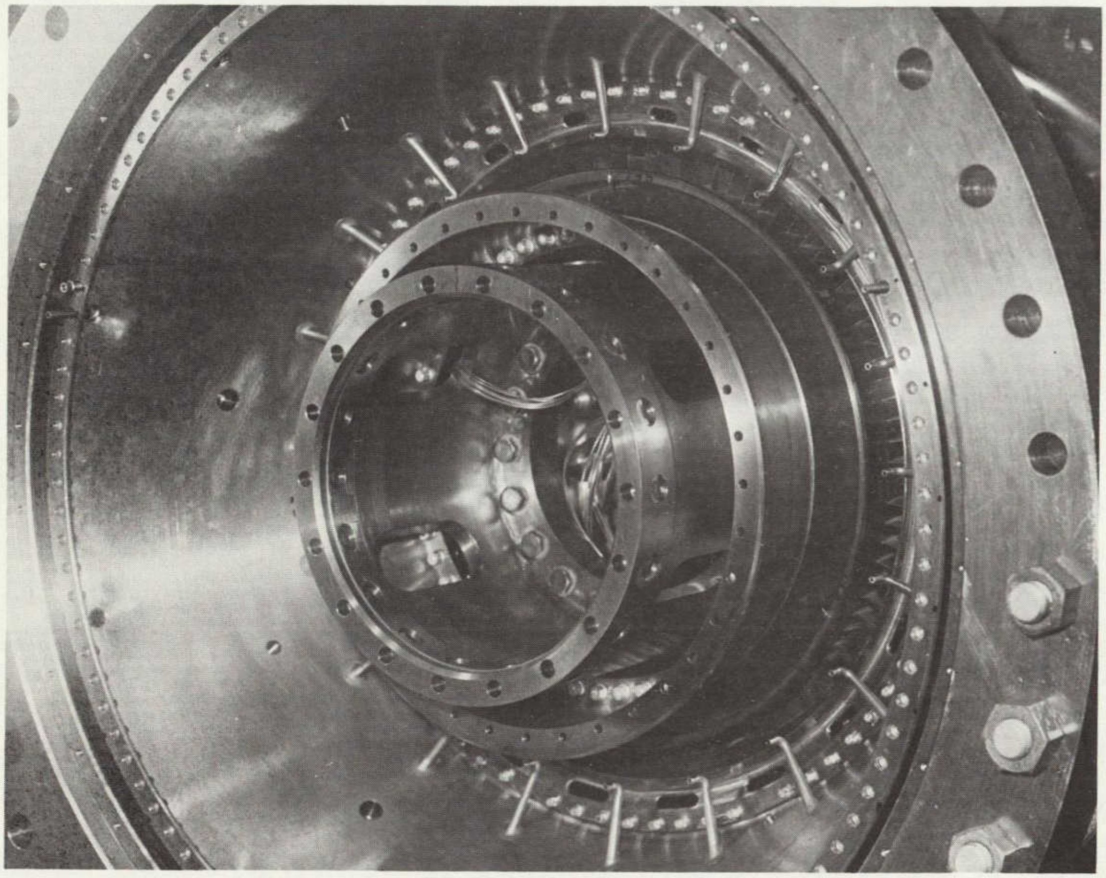


Figure 3. F101 Test Rig.

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the instrument spool. Each rake contained five elements. This instrumentation spool also contains water spray rings to cool the combustion gases downstream of the measurement plane. A photograph of the instrumentation spool section with the rakes installed is presented in Figure 4. Local gas samples were extracted and total pressures were measured using the gas sampling rakes shown.

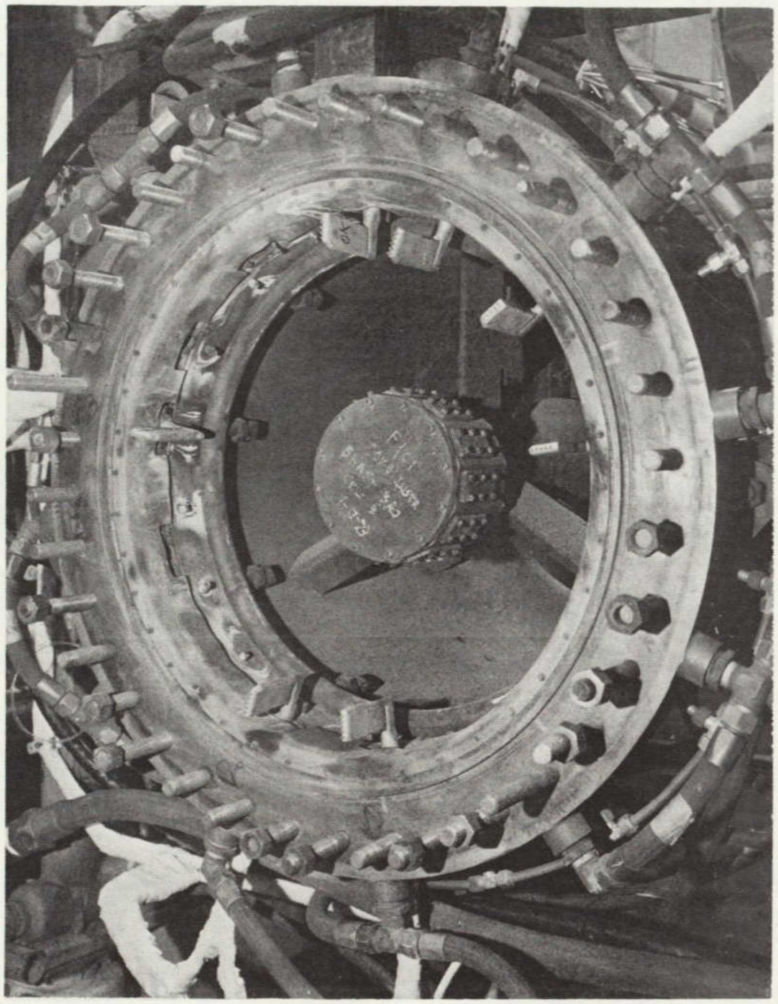

Figure 4. Instrumentation Spool.

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SECTION VI

DATA ACQUISITION AND REDUCTION

A. Pollutant Emissions Sampling and Analysis System

The exhaust gas sampling and analysis system used in this test program was designed to provide a rapid determination of the emission levels of the combustor configuration at a wide variety of test conditions. The sampling system consisted of a fixed rake assembly, multielement gas sampling probes, heated transfer lines, a manifolding valve panel and the various gas and smoke emissions analyzers.

The gas sample rakes used in this program contained five elements, or probes, with quick-quenching probe tips. In this design, both water cooling of the probe body and steam heating of the sample lines within the probe are used. A photograph of one of these rakes is shown in Figure 5. The assembly is shown schematically in Figure 6. Each of the five individual sampling elements was led out of the rake separately; there was no common manifolding of these sample lines within the sampling rake. The tips of each of these sampling elements were designed to quench the chemical reactions of the extracted gas sample as soon as the sample entered the rake. This quenching, or freezing, of the reactions was necessary to eliminate the possibility of further reactions within the sample lines. Water cooling of the rake body was required to maintain the mechanical integrity of the rakes in the high temperature, high pressure environment in which they operated. Steam heating of the sample lines within the rake, on the other hand, was needed to maintain these sample lines at a temperature high enough to prevent condensation of hydrocarbon compounds and water vapor within the sample lines.

With 10 sampling rakes with 5 elements each, a total of 50 gas sampling locations existed within the combustor exit plane. Of the 50 available probe elements used for gaseous emissions sampling, ten elements were alternately used for smoke emission sampling. A selector valve in these latter ten sample lines allowed either smoke level or gaseous emissions data to be obtained at any selected test condition. The individual rake elements normally used for the various types of measurements are shown in Figure 7. The exit pressure was measured by a single-element probe mounted in the combustor annulus.

Eight of the rakes have the five radial elements manifolded together, while the remaining two rakes had individual elements isolated to measure radial profiles. The gas sample lines were led to a series of selector valves and then to the emissions analyzers. These lines were grouped into bundles for each gas sample rake and steam traced from the individual rakes to the analyzers in order to maintain the sample line temperatures near 422° K. Each sample line was constructed of 0.64-cm diameter, 0.089-cm wall stainless steel tubing. Two thermocouples were installed in each tube bundle to monitor the temperature of the steam used for heating the sample lines. In addition, one sample line from each bundle was instrumented to provide a measurement

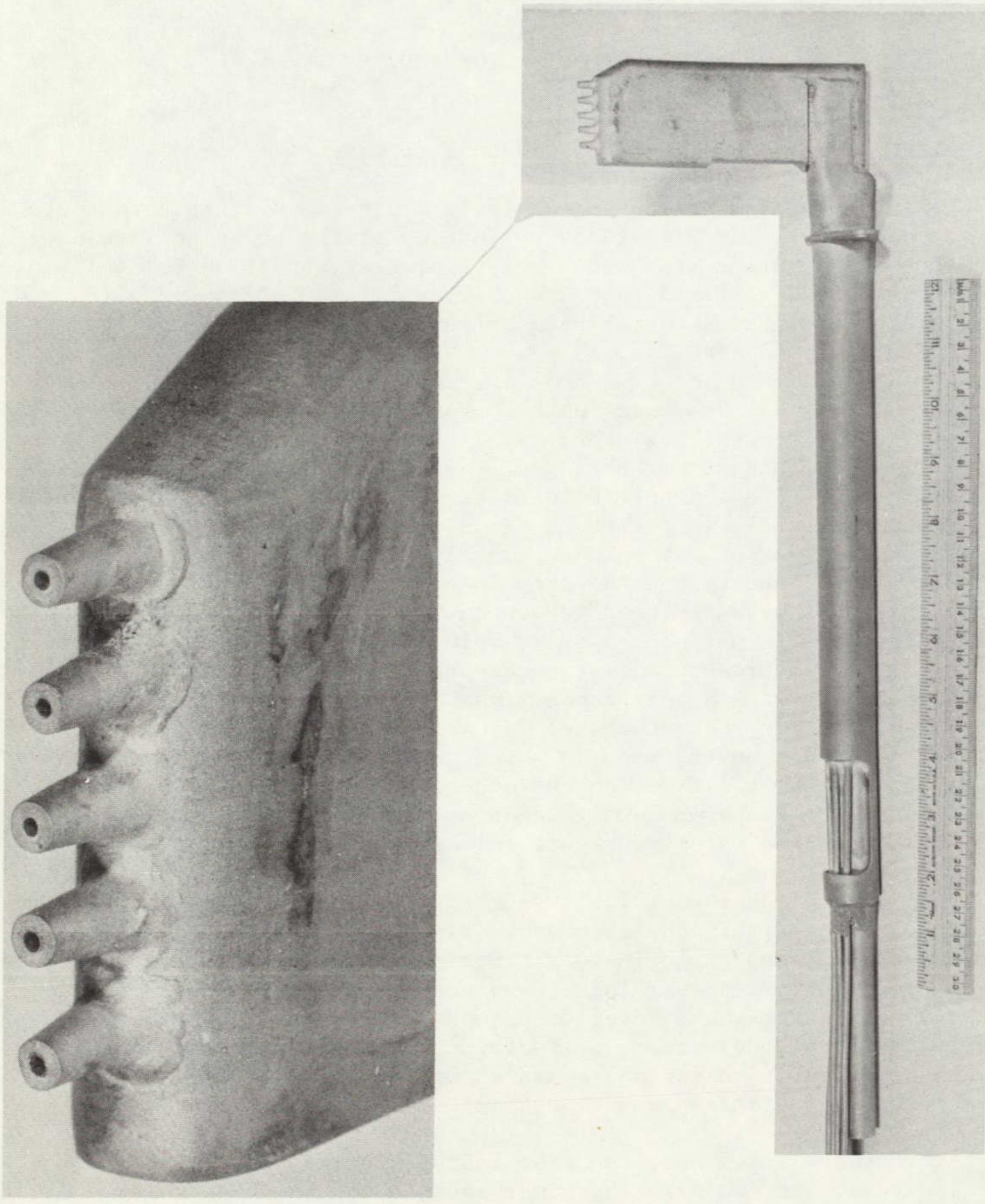


Figure 5. Gas Sample Rake Quick-Quenching Probe Tips.

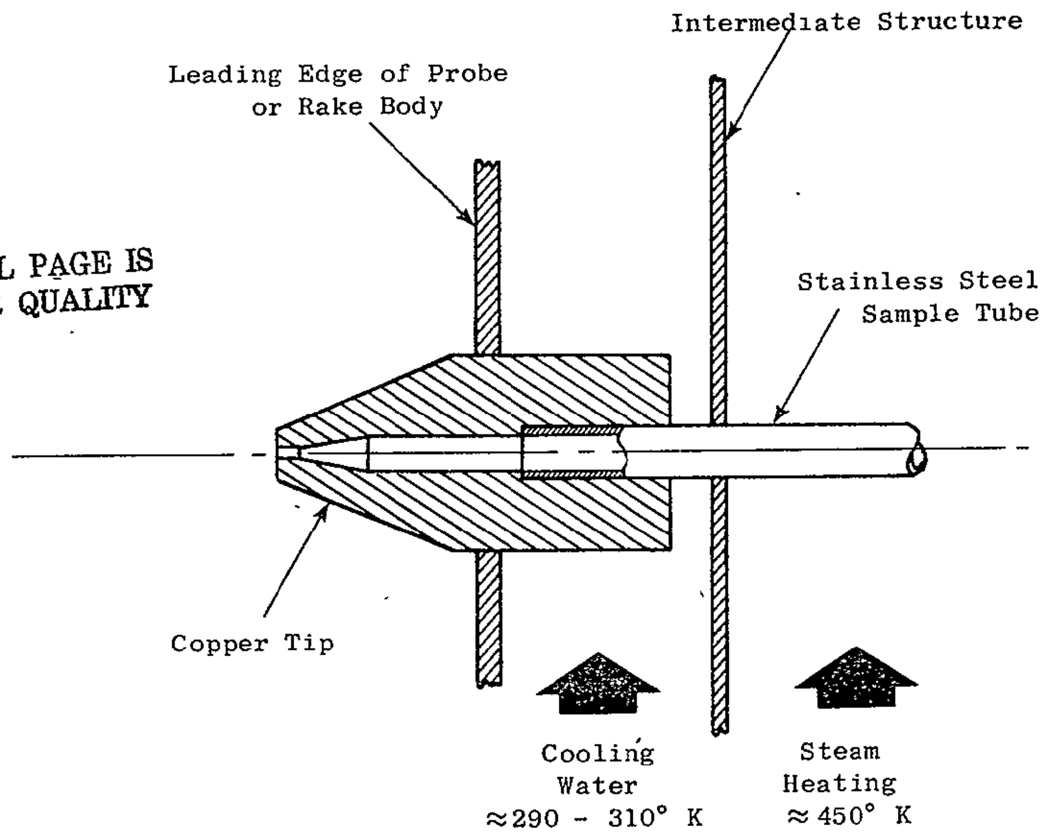
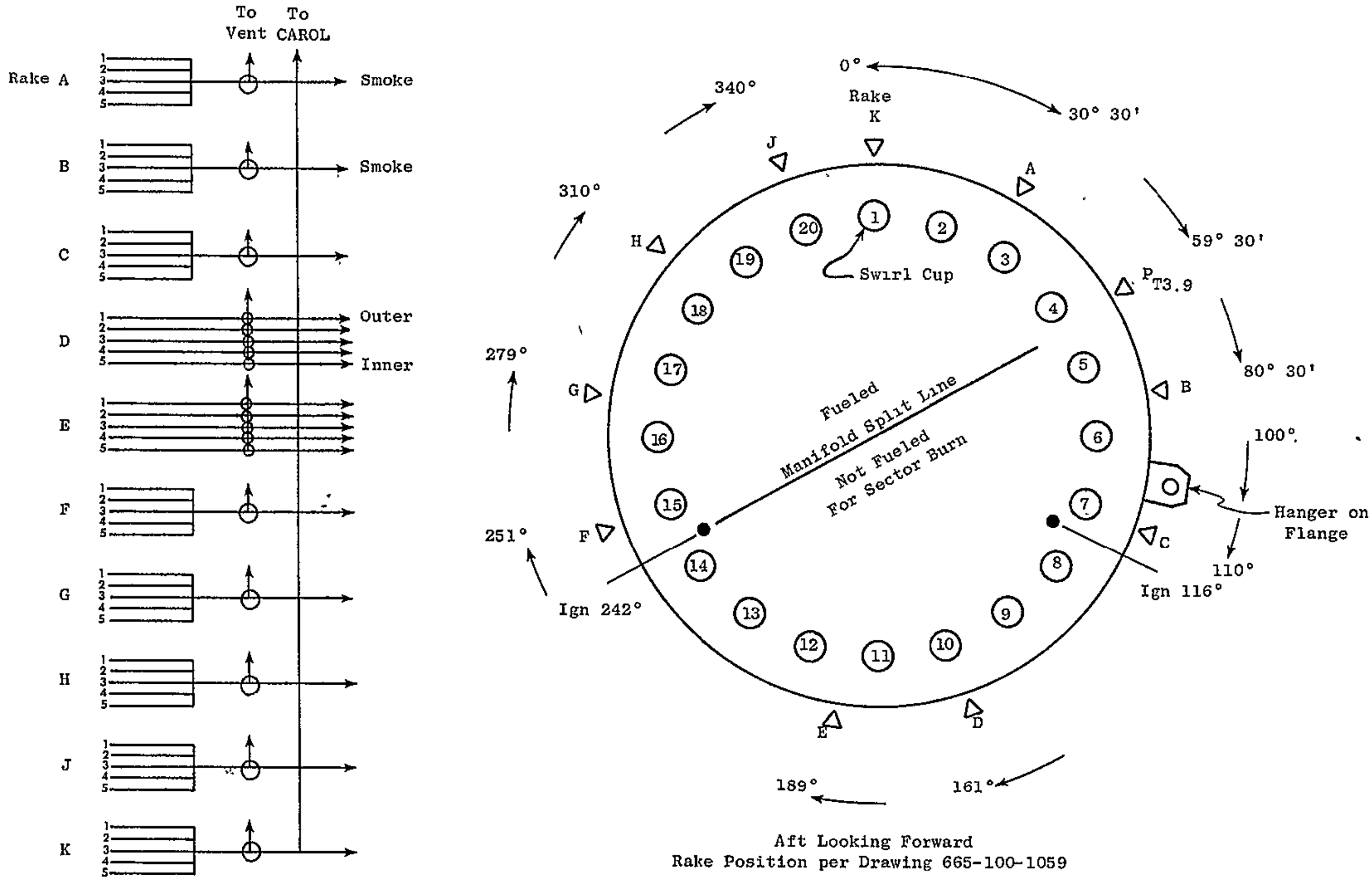


Figure 6. Steam-Heated, Water Cooled Gas Sample Rake Schematic.



Notes: 1. Manifold sample tubes of Rakes A, B, C, F, G, H, J, K at rakes.
2. $P_{T3.9}$ (Single Element)

Figure 7. Rake Location and Plumbing.

of the pressure within the sample line. This pressure measurement provided assurance that sufficient flow was being drawn through the sample lines to quench the reactions at the probe tips.

In the test cell control room, the 18 individual sample lines were connected to a group of 3-way selector valves. At this panel, the selected sample streams for providing smoke level were separated, by the valving arrangement, from those selected for gaseous emissions level determinations. By manipulation of the appropriate valves, any individual or manifolded elements, or any desired combination of elements, could be selected for the various types of measurements. The normal procedure used was to manifold the 18 selected streams shown in Figure 7 for gaseous emissions level determinations together at the control valve panel, thereby supplying one average gas sample to the emissions analyzers. This manifolding procedure provides a very fast method of determining the average level of each of the various emissions of interest and alleviates the need to analyze each sample individually at every test condition. At operating conditions of key importance individual rakes as well as radial samples were obtained as shown in Table III.

An existing on-line exhaust gas analysis system was used for determining the CO_2, CO, HC and NO_x concentrations of the exhaust gas sample streams. With this on-line system, the sample streams were continuously processed. A flow diagram of this system is shown in Figure 8.

The four basic gas analysis instruments of this on-line system are a flame-ionization detector for HC emissions, two nondispersive infrared analyzers for CO and CO_2 emissions, and a heated chemiluminescence analyzer for NO and NO_2 emissions. This analysis equipment is in general conformance with SAE ARP 1256 (Reference 1), except for the use of a chemiluminescence analyzer for NO_x emissions. The output of these analyzers were recorded both on strip-chart paper and onto hand-logged data acquisition sheets.

The smoke emissions data were obtained in this program using the standard General Electric filter-stain method. The equipment used for these measurements is in conformance with SAE ARP 1179 (Reference 2).

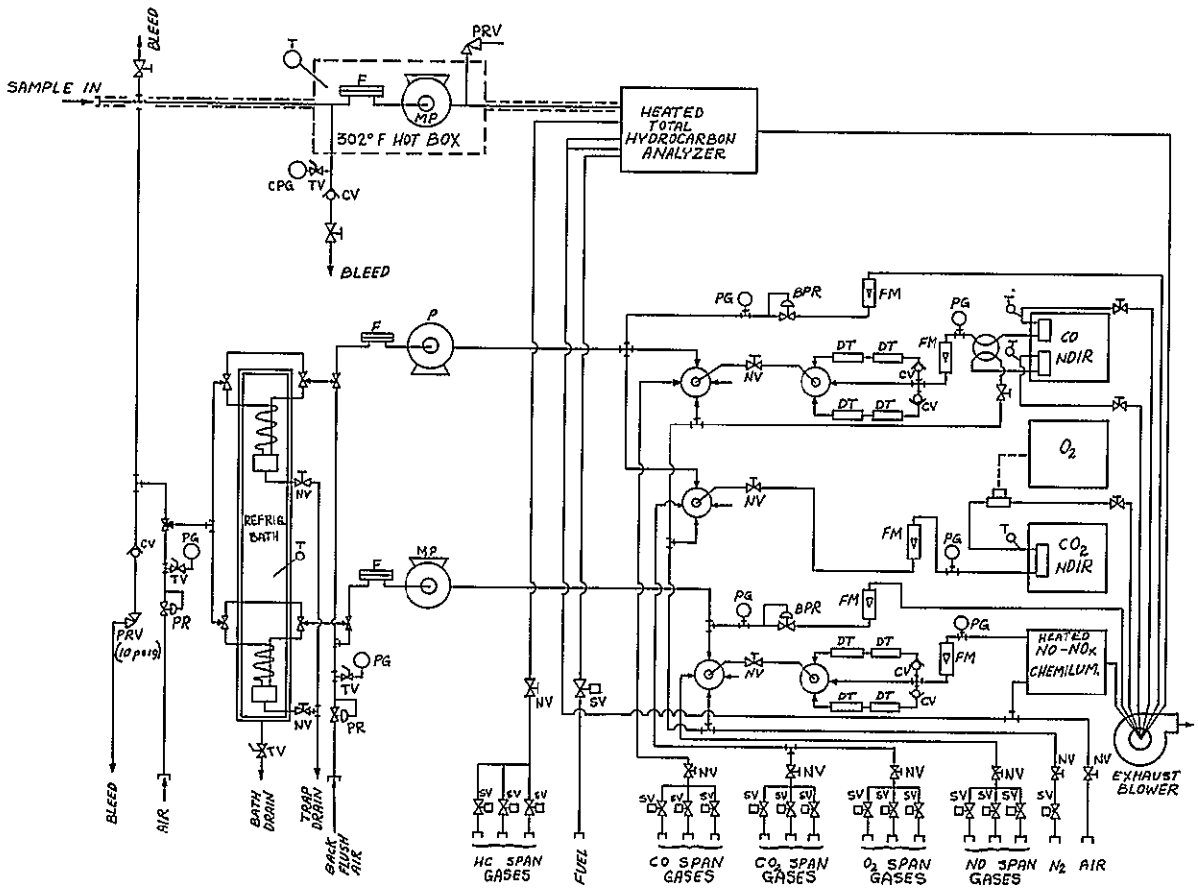
B. Combustor Performance Data Processing Systems

The data processing equipment permanently installed in Test Cell A3 includes a 900-channel digital data acquisition system, strip-chart recorders for continuous recording of up to 24 test parameters, displays of 22 pressures, displays of 24 temperatures and displays of 4 fuel flows for use by the operators in controlling test parameters; plus a small analog computer generally programmed to compute airflows and fuel/air ratios. Portable equipment includes a teletype terminal for the time-sharing computers. The valves used to regulate fuel flows, airflows, combustor air temperatures and combustor air pressures are remotely operated from the control room by means of pneumatic operators.

Throughout the combustor test, data were recorded by the test cell digital data acquisition system. This apparatus scans each of the measured parameters

Table III. Sampling Modes.

Sample Mode	Description	Total No. Elements	Elements Each Sample	Number Sample
I	Short sample - gang Rakes A, B, C, D, E, F, G, H, J and K.	50	50	1
II	Gang Rakes D and E by immersion. D1-E1, D2-E2, D3-E3, D4-E4 and D5-E5.	10	2	5
III	Gang each rake - A, B, C, D, E, F, G, H, J, K.	50	5	10
IV	Rakes D and E by immersion. D1, D2, D3, D4, D5, E1, E2, E3, E4 and E5.	10	1	10



LEGEND

BPR	-	Back Pressure Regulator
CPG	-	Compound Pressure Gage
CV	-	Check Valve
DT	-	Dryer Tube
F	-	Filter
FM	-	Flowmeter
MP	-	High Temperature Metal Bellows Pump-Mounted in Inverted Position
NV	-	Needle Valve
P	-	Pump
PG	-	Pressure Gage
PR	-	Pressure Regulator
PRV	-	Pressure Relief Valve
SV	-	Solenoid Valve
T	-	Temperature Indicator
TV	-	Toggle Valve

Figure 8. General Electric On-Line Exhaust Emissions Analysis System, Flow Diagram.

in sequence, controlling the position of pressure scanning valves when required, converts the amplified DC signal of the measurement to digital form and records the value on a perforated paper tape suitable for input to the time-sharing computer through the teletype terminal. During each scan, the overall voltage accuracy is checked against a precision potentiometer that has been calibrated in a standards laboratory. The digital voltmeter and low level amplifier are of sufficient quality that voltages are accurate to 0.02 percent of full-scale in the 0.-10 millivolt range.

All connections between data sensors and readout instrumentation, and all programming of the sequencing and control circuitry, were accomplished through interchangeable program boards. Thus, each test setup includes its own prewired, preprogrammed front panel for rapid changeover from one circuit configuration to the next. A schematic of the data acquisition installation setup is shown in Figure 9.

C. Test and Emissions Data Analysis Procedures

The gas sampling system developed for these tests incorporated the latest in gas sample extraction and automated data processing systems technology and was based on the experience gained in numerous combustor component test programs conducted at General Electric. Detailed data were acquired at the combustor exit plane at all test conditions to accurately determine the emissions and performance characteristics of this combustor configuration. These test procedures, along with the analytical procedures used to reduce and adjust the test data to standard QCSEE UTW and OTW engine operating conditions, are described in the following sections.

1. Test Conditions

The test conditions selected for this combustor evaluation represented actual engine operating conditions and parametric variations about these operating conditions. The points which were most important during this test were the QCSEE UTW and OTW engine standard day conditions of 4.5% power (ground idle), 30% power, 85% power and 100% power (sea level takeoff) because the emissions indices for the applicable EPA standards are specified at these cycle points. Other points of particular interest were a 3% power idle condition, 10% power idle condition, and 65% power approach condition. In addition, selected emission reduction approaches including sector burning and simulated compressor bleed extraction were evaluated.

In this test, the combustor inlet temperatures, combustor inlet pressure and combustor airflow rates of the QCSEE UTW and OTW engines were exactly duplicated. Turbine cooling airflow and compressor bleed extraction rates were not duplicated in these tests. Earlier rig tests of this combustor design where the effects of turbine cooling flow on emissions were evaluated indicated no impact on emissions characteristics. Therefore, substantial amounts of test time required for simulating these flows was eliminated.

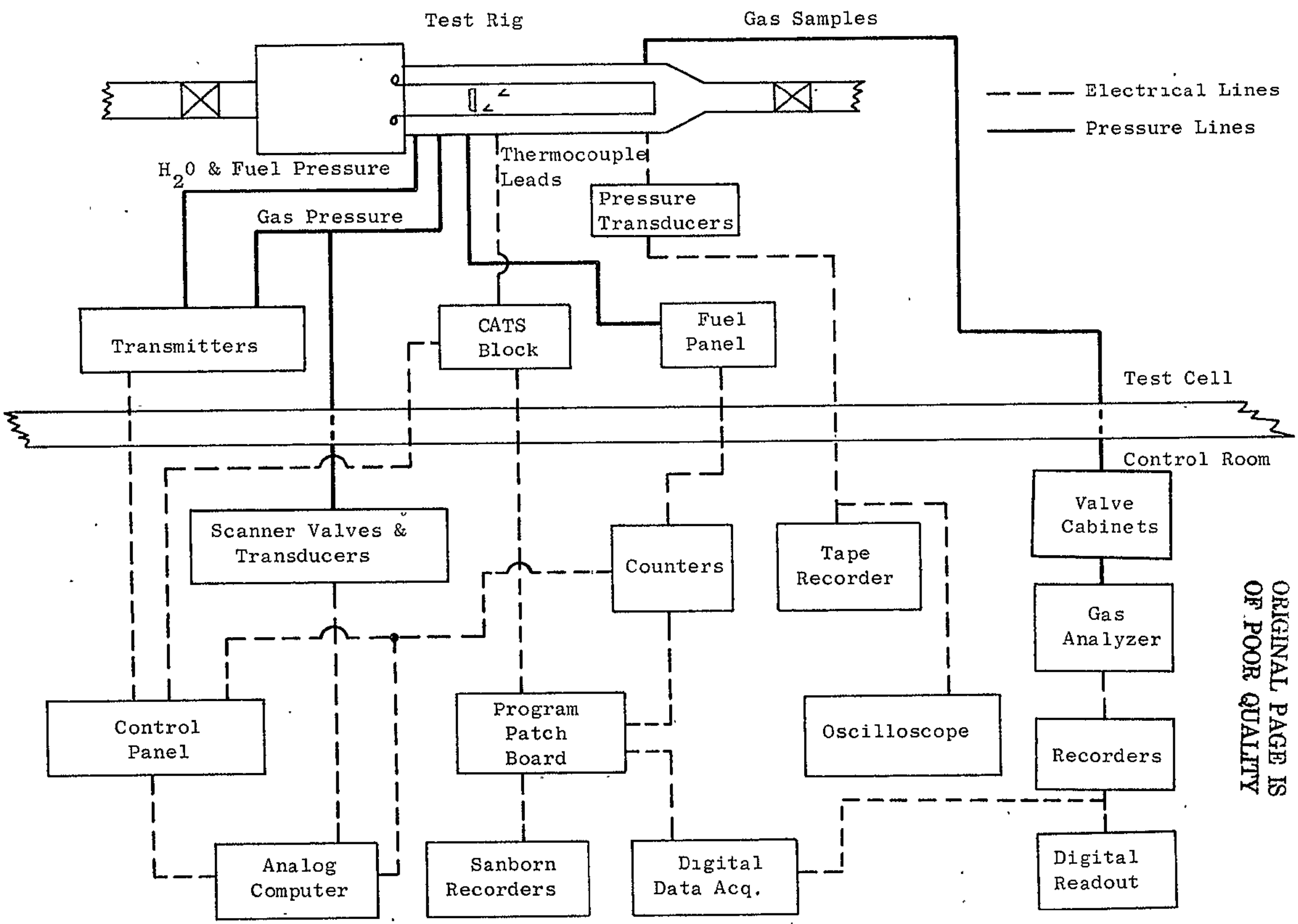


Figure 9. Test Facility Data Acquisition Schematic.

The combustor configuration for the QCSEE UTW and OTW engines was tested over ranges of test conditions from below nominal idle to takeoff operating conditions. The test conditions investigated are shown in the test plan of Table IV.

2. Test Procedures

The test points were run in order of increasing combustor inlet temperature for safety considerations and to expedite testing. As test conditions were changed, the combustor pressure drop and the various combustor metal temperatures were monitored on multichannel strip-chart recorders to ensure that the established transient safety limits were not exceeded. When each test condition was set and stabilized, the data were recorded in two phases. First, the fixed combustor instrumentation (inlet air pressure and temperature, airflow, fuel flow, metal temperatures, exit pressure, etc.) was recorded. Then a recording of the pollutant emissions data at numerous positions in the combustor exit plane was made. The scope of the test instrumentation read on each test point is shown in Table V.

The normal test procedure was to obtain combustor performance data and then record emissions from the ten rakes in the sampling mode specified in the test plan.

3. Pollutant Emissions Measurement Procedures

As is described in the preceding section, 50 individual elements (5 elements per rake) were usually used for the gaseous emissions level measurements. Because of the extensive amount of time that would have been required to individually analyze samples obtained from each of these elements at every combustor test point, sample manifolding was employed as shown on Figure 7. Previous combustor component test programs at General Electric have shown that, when done properly, the sample-manifolding concept provides emissions levels that are in close agreement with those determined from measurements of many individual samples.

CO, CO_2, C_xH_y and total NO_x emissions levels were determined in all instances. Additional details on these gaseous emissions sampling procedures are presented in Reference 3.

Smoke emissions levels were also measured at selected test points of interest. At those conditions where smoke data were acquired, samples were usually extracted from the combustor exit plane with ten elements, as shown in Figure 7. These ten elements were manifolded together by rake to provide two average samples to the smoke measurement console. At least three smoke spots were taken at each test condition and the average SAE Smoke Number for this operating point was determined from the average of these three spots for each rake.

Table IV. Test Plan.

Test	Point No.	T_3 (° K)	P_3 (MN/m^2)	f_{36}	W_{36} (kg/sec)	W_f (kg/hr)	$(W_{36}/P_3)^2 T_3$ cm^4/sec^2 ° K	W_3 kg/sec	W_{BO+BI}* kg/sec	W_{BO}* kg/sec	* Sample Mode	Number of Samples	Smoke	Condition
Idle Emissions	1	378	0.18	0.021	3.80	288	1592.5	4.5	0.74	0.31	I	1		3% UTW idle
	2	377	0.17	0.032	3.14	358	1157.8	3.8	0.61	0.48	I	1		3% UTW idle with bleed
	3	406	0.23	0.011	5.03	200	1909.8	6.1	1.04	0.43	I	1		4.5% UTW idle with bleed
	4	406	0.23	0.0175	5.03	318	1909.8	6.1	1.04	0.43	I,II,III	16	X	4.5% UTW idle with bleed
	5	406	0.23	0.025	5.03	454	1909.8	6.1	1.04	0.43	I	1		4.5% UTW idle with bleed
	6	406	0.23	0.032	5.03	581	1909.8	6.1	1.04	0.43	I	1		4.5% UTW idle with bleed
	7	406	0.23	0.025	4.32	395	1413.8	5.2	0.90	0.32	I	1		4.5% UTW idle with bleed
	8	507	0.51	0.011	10.84	429	2194.0	13.1	2.27	0.94	I	1		10% UTW idle
	9	507	0.51	0.0149	10.84	581	2194.0	13.1	2.27	0.94	I,II,III	16	X	10% UTW idle
	10	507	0.51	0.020	10.84	779	2194.0	13.1	2.27	0.94	I	1		10% UTW idle
	11	507	0.51	0.025	10.84	974	2194.0	13.1	2.27	0.94	I	1		10% UTW idle
	12	417	0.25	0.0159	5.58	319	1994.2	6.7	1.13	0.47	I,II,III	16	X	4.5% OTW idle
	4	406	0.23	0.0175	5.03	318	1909.8	6.1	1.04	0.43	I	1		4.5% UTW idle (repeat)
Sector Burn	201	406	0.23	0.0055	5.03	100	1909.8	6.1	1.04	0.43	III	10		4.5% UTW idle
	202	406	0.23	0.0082	5.03	159	1909.8	6.1	1.04	0.43	III	10		4.5% UTW idle
	203	406	0.23	0.0125	5.03	227	1909.8	6.1	1.04	0.43	III	10		4.5% UTW idle
	204	406	0.23	0.016	5.03	290	1909.8	6.1	1.04	0.43	III	10		4.5% UTW idle
	205	406	0.23	0.0125	4.33	195	1413.8	5.2	0.90	0.32	III	10		4.5% UTW idle with bleed
	206	417	0.25	0.008	5.53	159	1994.2	6.7	1.13	0.47	III	10		4.5% OTW idle
High Power	100	624	1.01	0.0230	18.4	1523	2001.8	22.2	3.81	1.58	I,II	6	X	30% UTW CFS
	101	641	1.17	0.0247	21.0	1868	1979.4	25.3	4.31	1.79	I	1	X	65% UTW CFS
	102	660	1.30	0.0267	22.8	2193	1938.0	27.5	4.72	1.96	I,II	6	X	85% UTW CFS
	103	684	1.43	0.0294	24.2	2562	1876.3	29.2	4.99	2.07	I,IV	11	•X	100% UTW CFS
	104	532	0.64	0.0152	13.4	734	2220.1	16.2	2.77	1.15	I	1	X	30% UTW CFP
	105	612	1.05	0.0217	19.5	1524	2046.9	23.6	4.04	1.68	I	1	X	65% UTW CFP
	106	554	0.74	0.0158	15.1	862	2235.2	18.1	3.04	1.26	I,II	6	X	30% OTW
	107	726	1.72	0.0309	28.4	3160	1901.0	34.2	5.81	2.41	I,IV	11	X	100% OTW
	104	532	0.64	0.0152	13.4	734	220.1	16.2	2.77	1.15	I	1	X	30% UTW CFP (repeat)

*Turbine cooling flows and CDP bleed flows simulated by variable combustor flow

Table V. Combustor/Rig Instrumentation.

Parameter	Instrumentation
Total Airflow	Standard ASME Orifice
Fuel Flow	Turbine Flow Meters
Fuel Injector Pressure Drop	Pressure Tap in the Fuel Manifold
Fuel Temperature	Thermocouple in Fuel Manifold
Diffuser Inet Total Pressure	2 One-Element, Fixed-Impact Rakes
Diffuser Inlet Total Temperature	6 Thermocouples on 2-3 Element Rakes
Combustor Exit Emissions Levels	10 Five-Element Impact Rakes
Combustor Exit Total Pressure	1 Element on Total-Pressure Rake
Combustor Metal Temperature	10 Thermocouples on Liners
Inlet Air Humidity Level	Dew Point Hygrometer
Combustor Passage Static Pressure	5 Wall Taps in Each Passage (10 Total)
Combustor Dome Pressure Drop	4 Pressure Taps

4. Combustor Performance Data Processing Procedures

A summary of the important combustor operating performance parameters which were measured or calculated is shown in Table VI. Most of the parameters and equations of this table are self-explanatory.

The voltage responses of the CO, CO_2, C_xH_y and NO_x analyzers were recorded on strip-chart recorders and transcribed to emissions test log sheets for calculation of the emissions concentrations. These data were then input to a computer data reduction program for calculation of the emission indices, the combustion efficiency and the fuel/air ratio of the gas sample at each test point.

The equations used for these calculations were basically those contained in SAE ARP 1256 (Reference 1). In these calculations, the CO and CO_2 concentrations were corrected for the removal of water from the sample before its analysis. Aviation kerosene (JP-5 fuel) was used throughout the test. Therefore, a typical value for n (fuel hydrogen-to-carbon atom ratio) of 1.92 was used in these calculations. Fuel analyses, obtained from a fuel sample during this test, confirmed this value.

Based on the individual gas sample emission index, fuel/air ratio and combustion efficiency values at each rake location, the overall average emission indices, sample fuel/air ratio, and combustion efficiency for the test condition were then determined for modes III and IV by mass averaging. These averaged values are the values presented in the numerous data tables and figures throughout this report.

Table VI. Summary of Measured and Calculated Combustor Parameters.

Parameter	Symbol	Units	Measured	Calculated	Value Determined From
Inlet Total Pressure	P_{T_3}	N/m^2 (atm)	X		Avg. of measurements from 1 immersion on 2 rakes (2 total)
Exit Total Pressure	$P_{T_{3.9}}$	N/m^2 (atm)	X		Avg. of measurements from 1 immersion on 1 rake (1 total)
Total Pressure Loss	$\Delta P_T/P_{T_3}$	%		X	$100\ (P_{T_3} - P_{T_{3.9}})/P_{T_3}$
Total Inlet Airflow	W_3	kg/sec	X		ASME orifice
Combustor Bleed Airflow	W_{bleed}	kg/sec		X	W_c/W_3 cycle deck
Combustor Airflow	W_c	kg/sec	X		ASME orifice
Total Fuel Flow	W_f	kg/hr	X		Turbine flowmeter
Overall Metered Fuel/Air Ratio	f_m	-		X	$W_f/3600\ W_c$
Inlet Air Humidity	H	g/kg	X		Dew point hygrometer
Inlet Total Temperature	T_{T_3}	° K	X		Avg. of measurements from 3 immersions on 2 rakes (6 total)

SECTION VII

TEST RESULTS

A. Test Plan

The proposed test plan, as shown in Table IV, was to measure the combustor emissions levels at the QCSEE engine cycle operating conditions, as specified in the EPA Standards; namely, ground idle, 30%, 85% and 100% of takeoff thrust for both the UTW and OTW engines. In addition to these specific conditions, the effects of combustor fuel/air ratio, simulated CDP bleed, and ten-cup sector burning on idle emissions were also evaluated at UTW engine idle conditions. The test points planned versus those accomplished for both the UTW and OTW test conditions are compared in Table VII. Test conditions were maintained very close to those prescribed in the plan except for some points at the beginning of the test and two test points during sector burning. The actual F101 PFRT combustor tested in this program is shown in Figure 10 in its pretest condition. A total of 19.5 hours of burning time were accumulated while acquiring 265 gas samples and 23 smoke readings.

B. Overall Test Results

A summary of the emissions test data and the corresponding combustor operating conditions are shown in Table VIII (Sheets 1 and 2). The emissions values shown are the fuel/air weighted averages for the individual data sources. The column titled Emission Index NO_x is the measured data and the one titled Engine NO_x is the NO_x emissions index corrected to a standard humidity of 44 grains per pound of air.

C. Idle Emissions Test Results (Test Plan Points 1-12)

1. Full-Annular Burning Results

Because of the high thrust levels associated with multiengine STOL type aircraft, an idle power setting of 3% of SLTO thrust in lieu of the normal 4.5% idle power has been considered for the QCSEE UTW and OTW engines. As part of this component test, the emissions levels of the combustor were measured for a UTW engine 3% idle condition with and without compressor discharge bleed (CDP) in addition to the normal 4.5% idle engine operating conditions.

As expected, at these very low power settings where the combustor inlet temperatures and pressures are low, resulting in unfavorable combustion zone conditions, the idle emissions were quite high. At the UTW 3% idle condition, CO and C_xH_y emissions levels of 142 g/kg of fuel and 42 g/kg of fuel, respectively, were measured. With a simulated CDP bleed level of approximately 19% W_3, the CO and C_xH_y emissions were reduced 25% and 47%, respectively.

Table VII. QCSEE Component Test Point Summary.

	Planned UTW	Planned OTW	Accomplished UTW	Accomplished OTW
Idle Emissions				
• Inlet Temperature Variation				
T_3 = 378 ° K	2		2	
= 406	5		5	
= 415		1	1	1
= 437			2	
= 507	4		4	
• CDP Bleed Simulation	2		2	
• Sector Burning	5	1	6	1
• Repeat Data	1		4	1
• LBO and Ignition			1	
High Power Emissions				
• Operating Line	6	2	6	2
• Repeat Data	1		1	
Total Planned	24	4		
Total Accomplished			33	5

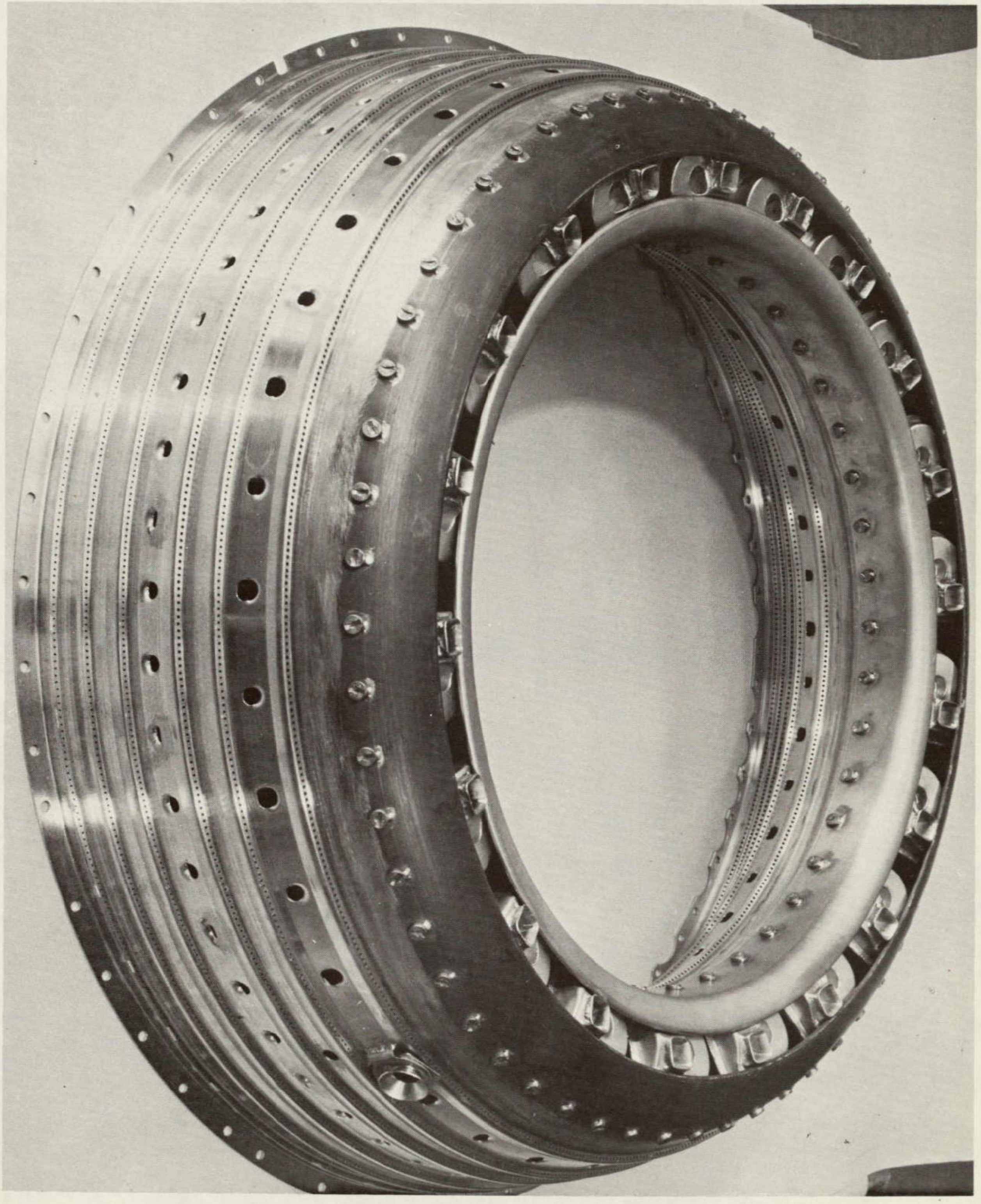


Figure 10. F101 PFRT Combustor Test Hardware.

Table VIII. Summary of Test Results.

Reading Number	Inlet Total Pressure (MN/m^2)	Inlet Total Temperature (° K)	Combustor Airflow (kg/sec)	Total Fuel Flow (kg/hr)	Total Air Flow (kg/sec)	Fuel/Air Ratio Metered: P_f (kN/m^2)	f_s/f_m	Overall	Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NO_x	Engine NO_x	SAE Smoke Number	Total Press. Loss %	Dome Press. Loss %	Sample Mode	Test Plan Points	Power Setting
1																			
2	0.184	402	3.834	286.3	3.834		1.086	0.0207	93.64	137.8	31.4	1.2	1.2113		0.0533	0.0439	I	1	
3	0.182	377	3.637	290.2	3.637	983.9	1.092	0.0222	92.53	141.7	41.6	1.1	1.1104		0.0465	0.0389	I	1	3% UTW
4	0.177	374	2.922	361.2	2.922	988.4	1.088	0.03434	95.35	105.7	21.9	1.2	1.2113		0.0323	0.02595	I	2	3% UTW Bld.
5	0.232	409.1	4.922	202.8	4.972	979.7	1.038	0.01133	93.06	128.9	39.3	1.8	1.8170		0.0571	0.0505	I	3	4.5% UTW
6	0.230	408.5	5.093	319.7	5.092	1025	1.118	0.01744	93.37	139.0	33.8	1.2	1.2113	3.850	0.0597	0.0518	I	4	
							1.153	0.01744	92.81	146.5	37.7	1.1	1.1104				II	4	
							1.120	0.01744	94.00	136.9	28.0	1.2	1.2113				III	4	
7	0.229	412.4	5.099	456.8	5.099	1043	1.102	0.02488	95.97	105.5	15.7	1.1	1.1104		0.0622	0.0521	I	5	
8	0.228	344.0	5.060	586.9	5.060	1114	1.111	0.03222	97.03	94.5	7.7	1.2	1.2113		0.0709	0.0544	I	6	
9	0.229	418.4	5.070	395.8	5.070	1018	1.113	0.0217	95.65	110.1	17.8	1.3	1.3123		0.0631	0.0531	I	45	
10	0.228	417.1	4.299	397.3	4.299	1020	1.091	0.02567	97.20	78.9	9.5	1.6	1.6151		0.0465	0.0375	I	7	4.5% W/Bld.
11	0.250	409.4	5.485	322.0	5.435	1046		0.1643							0.0580	0.0508			
12	0.250	415.1	5.420	320.9	5.420	1037	1.141	0.1645	94.08	122.8	30.5	1.6	1.6161	3.005	0.0591	0.0508	I	12	4.5% OTW
							1.172		93.89	129.6	30.8	2.3	2.3217				II	12	
							1.120		94.09	129.0	29.0	1.2	1.2113				III	12	
13	0.323	436.7	7.393	413.9	7.393	1144	1.165	0.01555	96.38	85.3	16.3	1.5	1.5142		0.0678	0.0604	I		CFM
14	0.509	505.6	10.752	431.8	10.751	1347	1.234	0.01115	99.04	28.3	3.0	3.5	3.5331		0.0573	0.0521	I	8	10% UTW
15	0.512	505.5	10.805	561.5	10.805	1404	1.137	0.01502	98.98	32.1	2.7	3.0	2.9088	1.495	0.0635	0.0580	I	9	
							1.202		99.08	28.4	2.6	4.0	3.8784				II	9	
							1.128		98.76	33.9	4.5	3.3	3.1996				III	9	
16	0.509	505.9	10.715	784.7	10.715	1462	1.170	0.02034	99.20	24.5	2.3	3.1	3.0057		0.0669	0.0594	I	10	
17	0.509	505.2	10.864	974.3	10.864	1515	1.196	0.0249	99.38	21.4	1.2	3.8	3.6844		0.0687	0.0584	I	11	
18	0.643	530.2	13.414	739.3	13.463	1580	1.159	0.01525	99.40	18.6	1.6	5.1	4.9449		0.0664	0.0586	I	104	30% UTW CFP
19	0.737	559.0	15.148	866.3	15.148	1708	1.149	0.01589	99.59	12.5	1.2	5.9	6.2591	5.967	0.0691	0.0611	I	106	30% OTW
							1.201		99.65	11.2	0.8	5.8	6.1530				II		
2	0.048	607.7	19.548	1527.1	19.548	2157	1.153	0.0217	99.84	5.1	0.4	7.7	7.5060	11.834	0.0650	0.0530	I	105	65% UTW CFP
3	1.005	623.4	18.648	1519.3	18.648	2123	1.176	0.02263	99.87	4.4	0.2	7.48	7.3	12.219	0.0634	0.0547	I		
							1.202		99.92	3.3	0.1	7.5	7.3111				II	100	30% UTW CFS

Table VIII. Summary of Test Results (Concluded).

Reading Number	Inlet Total Pressure (MN/m^2)	Inlet Total Temperature (° K)	Combustor Airflow (kg/sec)	Total Fuel Flow (kg/hr)	Total Air Flow (kg/sec)	Fuel/Air Ratio Metered			Sample Combustion Efficiency %	Emission Indices g/kg fuel				SAE Smoke Number	Total Press. Loss %	Dome Press. Loss %	Sample Mode	Test Plan Points	Power Setting
						P_f (kN/m^2)	f_s/f_m	Overall		CO	HC	NO_x	Engine NO_x						
4	1.177	642.0	21.553	1868.7	21.553	2.369	1.162	0.02408	99.91	3.2	0.1	8.6	8.3834	19.575	0.0726	0.0527	I	101	65% UTW CFS
5	1.311	661.9	23.355	2187.8	23.335	2.572	1.154	0.02604	99.94	2.3	0	9.9	9.6505	27.844	0.0736	0.0503	I	102	85% UTW CFS
							1.152		99.96	1.5	0	8.7	8.4808				II		
6	1.441	682.2	24.099	2560.2	24.099	2.801	1.127	0.02935	99.97	1.5	0	11.1	10.820	34.339	0.0728	0.0473	I	103	100% UTW CFS
							1.080		99.97	1.2	0	11.0	10.723				II		
7	1.728	722.8	27.680	3153.9	27.680	3.242	1.067	0.03165	99.98	0.9	0	14.5	13.946	43.575	0.0692	0.0475	I	107	100% OTW
							1.020		99.98	0.7	0	12.2	11.734			(D ave)	IV		
							1.074		99.98	1.0	0	11.4	10.965			(E ave)	IV		
8	0.646	534.9	13.274	739.3	13.294	1.584	1.178	0.01543	99.41	19.2	1.4	5.0	4.8090	2.703	0.0694	0.0569	I	104	30% UTW CFP
9	0.517	506.4	10.751	432.3	10.751	1.341	1.122	0.01117	98.68	35.3	5.0	4.6	4.4243		0.0736	0.0540	I	8	10% UTW
10	0.254	412.8	5.382	323.8	5.382	1.027	1.029	0.01671	93.50	136.0	33.3	2.0	1.9236		0.0648	0.0546	I	12	4.5% OTW
11	0.231	407.8	5.116	362.0	5.116	1.039	1.1262	0.01965	94.38	129.7	26.0	1.7	1.6351		0.0628	0.0529	I	3R	4.5% UTW
12	0.232	406.1	4.944	321.1	4.944	0.9928	1.104	0.01805	93.79	134.0	30.8	1.7	1.6351		0.0613	0.0475	I	4R	4.5% UTW
							1.121		94.14	133.6	27.5	1.7	1.6351				III		
13	0.229	402.8	4.903	203.7	4.903	0.9908	1.0572	0.01154	92.98	131.3	39.5	2.4	2.3083		0.0580	0.0459	I	3R	4.5% UTW
14	0.220	408.3	4.880	103.6	4.880	0.9866	1.302	0.0059	92.63	139.6	41.1	2.4	2.3083		0.0630	0.0446	I	201	Sector burn
							1.285		93.29	125.3	37.9	2.2	2.1160				III	201	
15	0.234	407.2	5.043	166.2	5.043	1.058	1.362	0.00915	94.68	111.8	27.1	2.2	2.1160		0.0669	0.0459	III	202	
16	0.233	407.2	4.981	230.4	4.981	1.100	1.404	0.01286	96.61	86.9	13 6	1.7	1.6351		0.0685	0.0429	III	203	
17	0.234	406.1	5.020	292.7	5.020	1.148	1.559	0.01620	97.45	77.0	7.5	1.4	1.3465		0.0691	0.0438	III	204	
18	0.233	406.1	5.079	198.7	5.079	1.065	1.400	0.01087	95.80	96.7	19.4	1.7	1.6351		0.0673	0.0470	III	205	
19	0.232	406.7	5.014	162.4	5.014	1.032	1.382	0.0090	94.89	105.8	26.4	1.8	1.7312		0.0707	0.0457	III	206	
20	0.323	440.0	7.661	417.0	8.863	1.139	1.128	0.01512	96.09	94.3	17.1	2.5	2.4045		0.0850	0.0722	I		

As part of the evaluation of UTW idle emissions characteristics at 4.5% idle, the combustor fuel/air ratio was varied from 0.011 to 0.032, a range which encompasses the design fuel/air ratio of 0.017 while maintaining the combustor inlet operating conditions. Due to some variation in combustor inlet operating conditions during evaluation of the UTW idle emissions, the emissions indices were adjusted to a common set of combustor inlet conditions to provide a better basis for comparison between annular and sector burning data. As shown in Figure 11, the CO and C_xH_y emissions indices are reduced from a level of 139 g/kg of fuel and 34 g/kg of fuel at design fuel/air ratio to 102 g/kg of fuel and 10 g/kg of fuel, respectively, at a fuel/air ratio of 0.032. This represents a 27% reduction in CO emission index and a 71% reduction in C_xH_y emission index. The OTW idle emissions were also evaluated at combustor operating conditions corresponding to a 4.5% idle power setting. At the design fuel/air ratio of 0.016, the CO and C_xH_y emissions indices were about 123 g/kg of fuel and 30 g/kg of fuel, respectively. Very good agreement between manifolded and individual-rake samples was obtained.

2. Sector Burning Results (Test Plan Points 201-206)

One of the proposed methods of obtaining reduced CO and C_xH_y emissions levels while maintaining constant-thrust engine operating conditions at idle is to fuel only a portion of the fuel injectors at the same overall fuel flow used for full-annulus burning. This produces a locally richer combustion zone which has demonstrated reduced emissions in other component and engine tests. In this test, ten adjacent fuel injectors out of the total 20 injectors were fueled to evaluate the effects of sector burning on idle emissions. This selection was based on the full-annular idle emissions data which indicated that the minimum CO level would be obtained at a local fuel/air ratio approximately twice the design level. As shown in Figure 11 with ten-cup sector burning, the CO emissions reached a minimum level of about 80 g/kg of fuel and a C_xH_y emission level of about 6.7 g/kg of fuel at the UTW engine idle condition. This represents a 38% reduction in CO emission index and a 78% reduction in C_xH_y emission index when changing the fueled mode from full-annular to ten-cup sector burning. The sector burning mode was generally lower in idle emissions than for full-annular burning at the same effective fuel/air ratio as shown in Figure 11. There is no direct explanation of these lower emissions based on the sample data, since the quenching at the unfueled boundaries should result in slightly higher emissions for the sector burning mode. The average emissions indices for individual samples did generally give lower results than for the manifolded sample mode. Also, based on fuel system calibration data, the sector burning portion of the fuel system had less cup-to-cup flow deviation (+1.7% to -1.6%) than for full-annular burning (+2.6% to -2.8%) which may have provided more uniform local combustion zone fuel/air ratios for the sector burning case. The resulting circumferential emissions profiles for the full-annular and sector burning configurations are shown in Figure 12. Sector burning with 14 out of 20 cups fueled has already been demonstrated on Engines 470-001/3A (F101 core) and 502-001/3A (CFM56), which are equipped with this combustor design, with no adverse operating effects.

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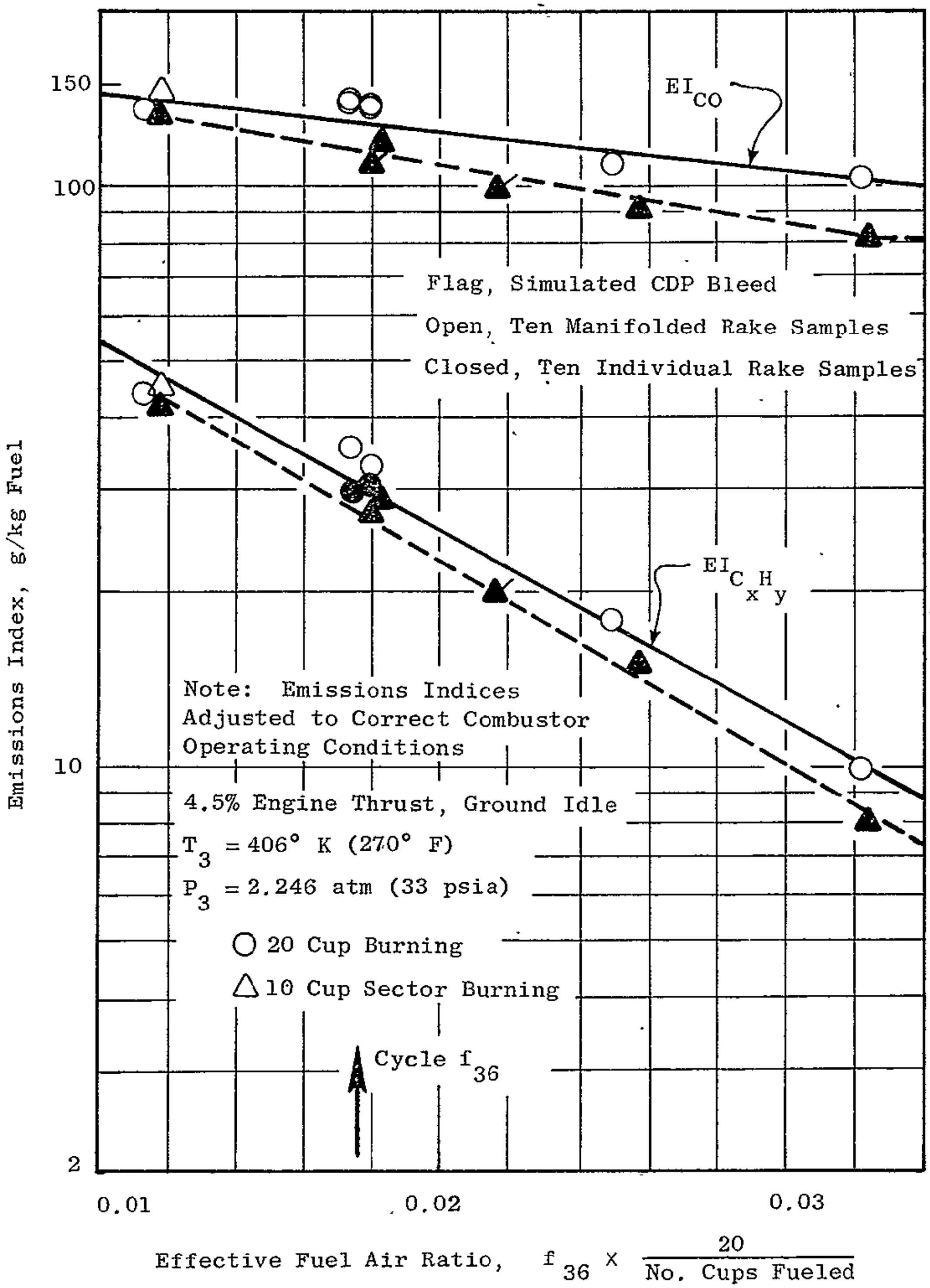

Figure 11. Under-the-Wing Engine Idle Emissions versus Combustor Metered Fuel/Air Ratio.

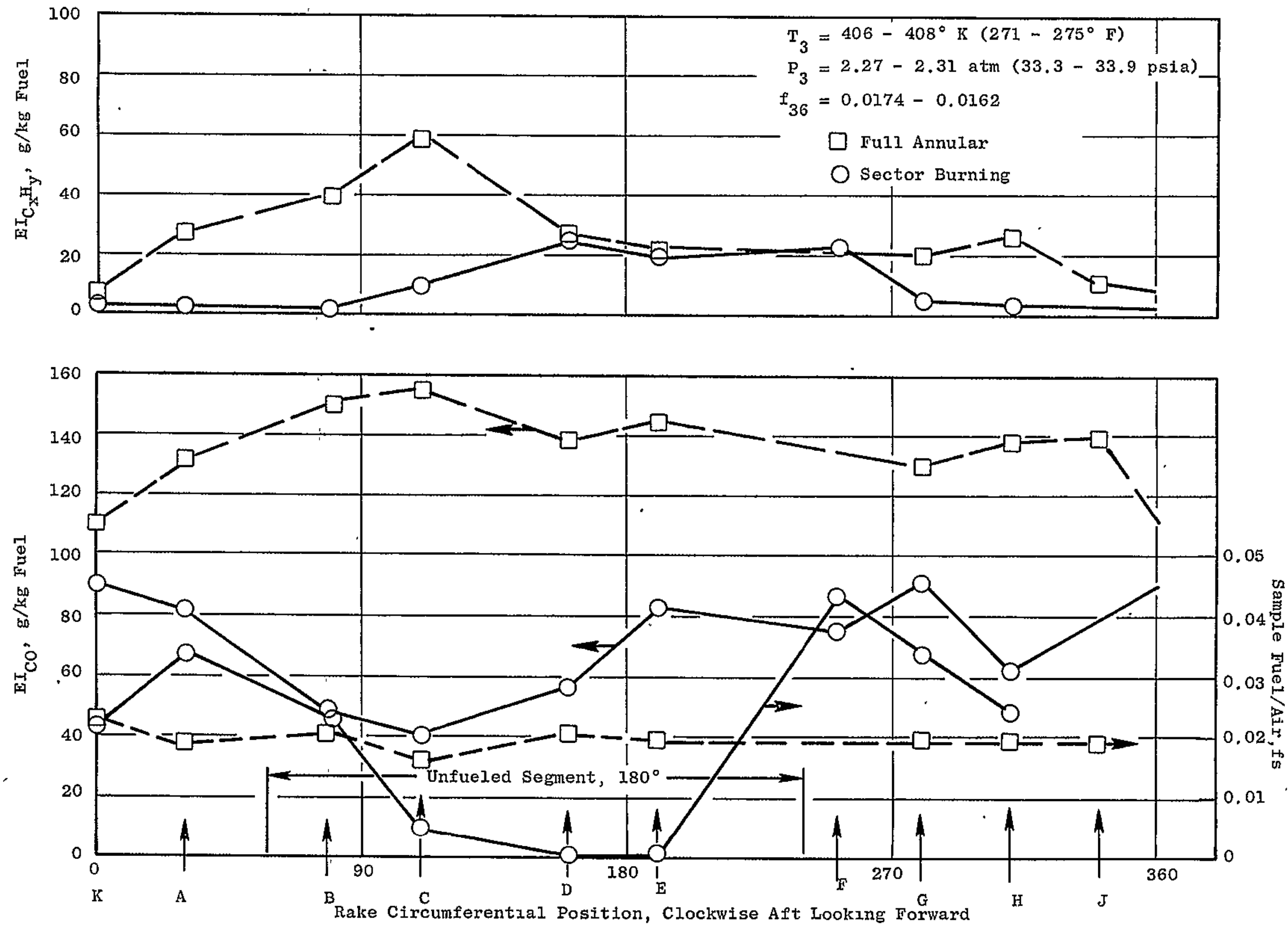

Figure 12. Under-the-Wing Idle Emissions, Circumferential Emissions Distribution for Full-Annular and Sector Burning.

As a part of these tests at UTW engine idle operating conditions, the use of CDP bleed extraction, where a portion of the compressor discharge air is dumped overboard (reducing the amount of air entering the combustor), was also investigated. This approach has been considered as a potential mode of engine operation to provide increased combustor fuel/air ratios at ground idle to reduce CO and C_xH_y emissions. Results similar to those obtained with sector burning were obtained. As shown in Figure 11, a CDP simulated bleed of approximately 16% W_3, which is equivalent to 16 cups burning, results in a 23% reduction in CO and a 33% reduction in C_xH_y.

An idle condition of 10% engine thrust was also evaluated to determine the sensitivity of idle emissions to combustor inlet temperature for this design. The results are shown in Figure 13. As anticipated, significantly reduced idle emissions, on the order of 74% for CO and 88% for C_xH_y were obtained for an increase in turbine inlet temperature and pressure of 355° K (180°F) and 282.7 N/m^2 (41 psi), respectively.

D. Engine Operating Line Emissions Test Results (Test Plan Points 100-107)

Emissions data were also acquired at the other prescribed QCSEE engine cycle conditions required for evaluating the EPA landing-takeoff cycle emissions parameters for comparison to the required 1979 EPA Standards. These test conditions included approach (30% power), climbout (85% power) and takeoff (100% power) for both the UTW and OTW engine cycles. In addition, the UTW, which has variable-pitch fan capability, was evaluated at test conditions corresponding to 30% and 85% power settings for both a constant fan-speed cycle and constant fan-pitch cycle. A 65% power condition, which is consistent with STOL aircraft approach conditions, was also tested.

Figure 14 shows the CO and C_xH_y emissions indices for the UTW and OTW, respectively, plotted against combustor inlet temperature (T_3). Both the CO and C_xH_y emissions indices agree very well with emissions data from previously conducted component tests of this combustor design. However, at identical T_3 values, the component test data are somewhat higher than has been obtained with other engines which are also equipped with this combustor design. It appears that in the engine, the combustor is actually operating at a higher fuel/air ratio than the value shown in the cycle deck. This higher fuel/air ratio appears to be the result of compressor discharge air bypassing the combustor through various leakage paths at idle conditions. As shown in Figure 11, lower CO and C_xH_y emissions levels would result for the engine if the combustor were operating at a higher fuel/air ratio than the cycle predicts. With sector burning, the effects of fuel/air ratio differences between rig and engine tests are largely eliminated since the optimum localized fuel/air ratio to obtain minimum CO and C_xH_y levels at idle is obtained with sector burning.

Prior to this component test series, the predicted CO and C_xH_y emissions levels of the UTW and OTW engines were based on earlier tests of an engine equipped with this combustor with full-annular burning. The effects of sector burning were based on component test results of the NASA Experimental Clean

10% Engine Thrust

T_3 = 506° K (450° F)

P_3 = 5.04 atm (74 psia)

Open, Ten Manifolded Rake Samples

Closed, Ten Individual Rake Samples

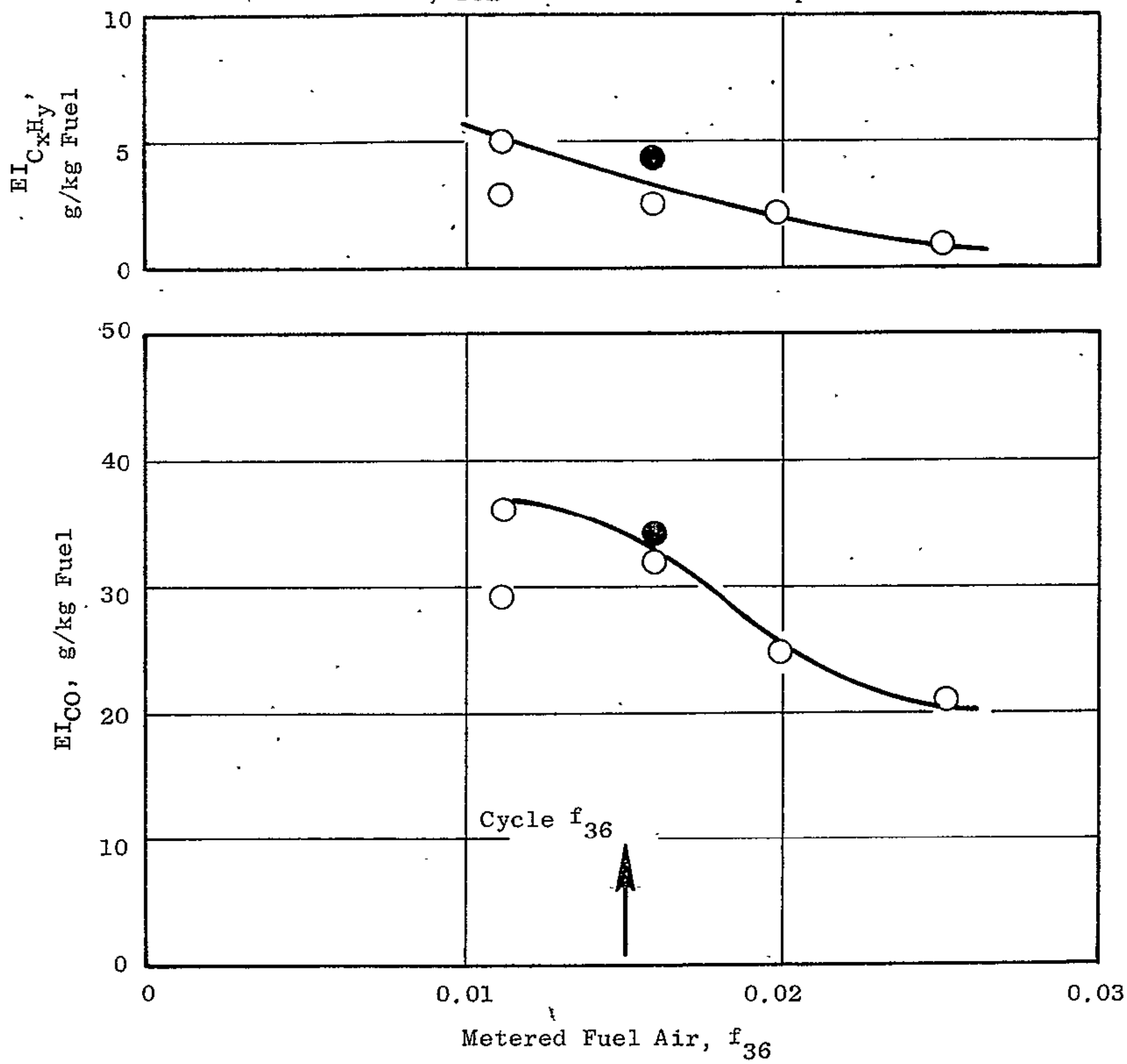

Figure 13. Under-the-Wing Idle Emissions versus Combustor Metered Fuel/Air Ratio.

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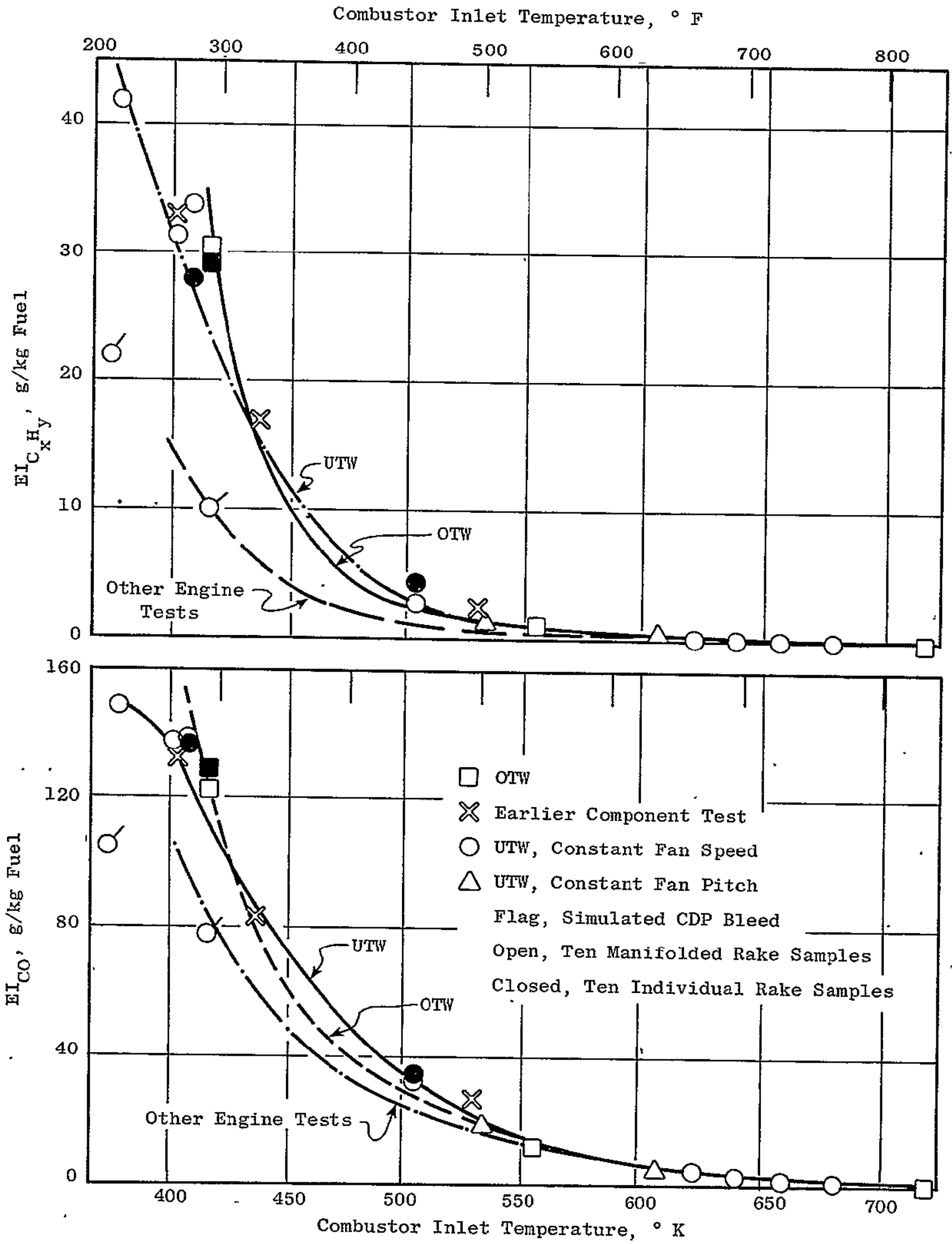

Figure 14. Under-the-Wing and Over-the-Wing CO and C_xH_y Emissions Indices versus Combustor Inlet Temperature.

Combustor Program (ECCP). In these ECCP sector burning tests of a CF6-50 combustor, where 180° of the combustor annulus was fueled, emissions reductions of 50% and 85% in CO and C_xH_y, respectively, were obtained. More recent tests of the CFM56 engine with both full-annular and sector burning have shown that the CO and C_xH_y emissions reductions obtained with a fuel/air ratio equivalent to ten-cup sector burning were on the order of 30% and 73%, respectively. These reductions were somewhat lower than the previous estimates based on the ECCP test results, and tend to substantiate the assumption that the engine operates at the higher fuel/air ratio than projected in the cycle deck. With the engine operating at a combustor fuel/air ratio 20% higher than the engine idle cycle value, the CO and C_xH_y emissions reductions estimates for ten-cup sector burning based on this component data would be about 35% and 79%, respectively; which agrees well with the engine idle emissions reductions data. Based on these QCSEE combustor component data and recent engine data, the previous predictions for the QCSEE UTW and OTW engines with sectorized fuel staging using earlier engine data appear to be too high. If indeed, the engine operating fuel/air ratio was higher than the cycle projection, the emissions levels reported would be lower than those at the cycle fuel/air ratio and subsequently, the amount of emissions reductions with sector burning before obtaining the optimum localized fuel/air ratio for minimum CO and C_xH_y levels at idle would be reduced. Therefore, emissions reductions with ten-cup sector burning on the order of 35% and 80% for CO and C_xH_y, respectively, rather than 50% and 85% as previously predicted would be more representative.

Figure 15 shows the NO_x emissions index, corrected to 44 grains/pound of air humidity, plotted against T_3 for the UTW and OTW engines. These emissions data are in good agreement with previously obtained component and engine test data. Because the UTW has a variable-pitch fan, two fan operating modes were selected for evaluation; namely, a constant fan-speed and constant fan-pitch mode. Since the core engine operating characteristics are not only different for the OTW and UTW in general, but also for the various UTW fan operating modes, a distinct set of combustor inlet conditions exist for each engine operating mode, which results in a unique NO_x characteristic in each case, as is shown in Figure 15. These NO_x variations at identical T_3 conditions are mainly attributed to the combustor inlet pressure and/or fuel/air ratio differences. The emissions of NO_x tend to increase with increased combustor inlet pressure (P_3) and decreased fuel/air ratio for rich dome combustors. The higher NO_x level of the UTW constant fan-pitch cycle is due to higher P_3 levels while the higher NO_x level of the OTW is due mainly to a lower combustor fuel/air ratio for identical cycle T_3.

The combustor exit SAE smoke number is plotted against combustor metered fuel/air ratio in Figure 16. The smoke numbers measured were unexpectedly high; however, the dome stoichiometry of this combustor, at QCSEE UTW and OTW engine takeoff conditions, is much richer than in the F101 and other engine applications as shown below:

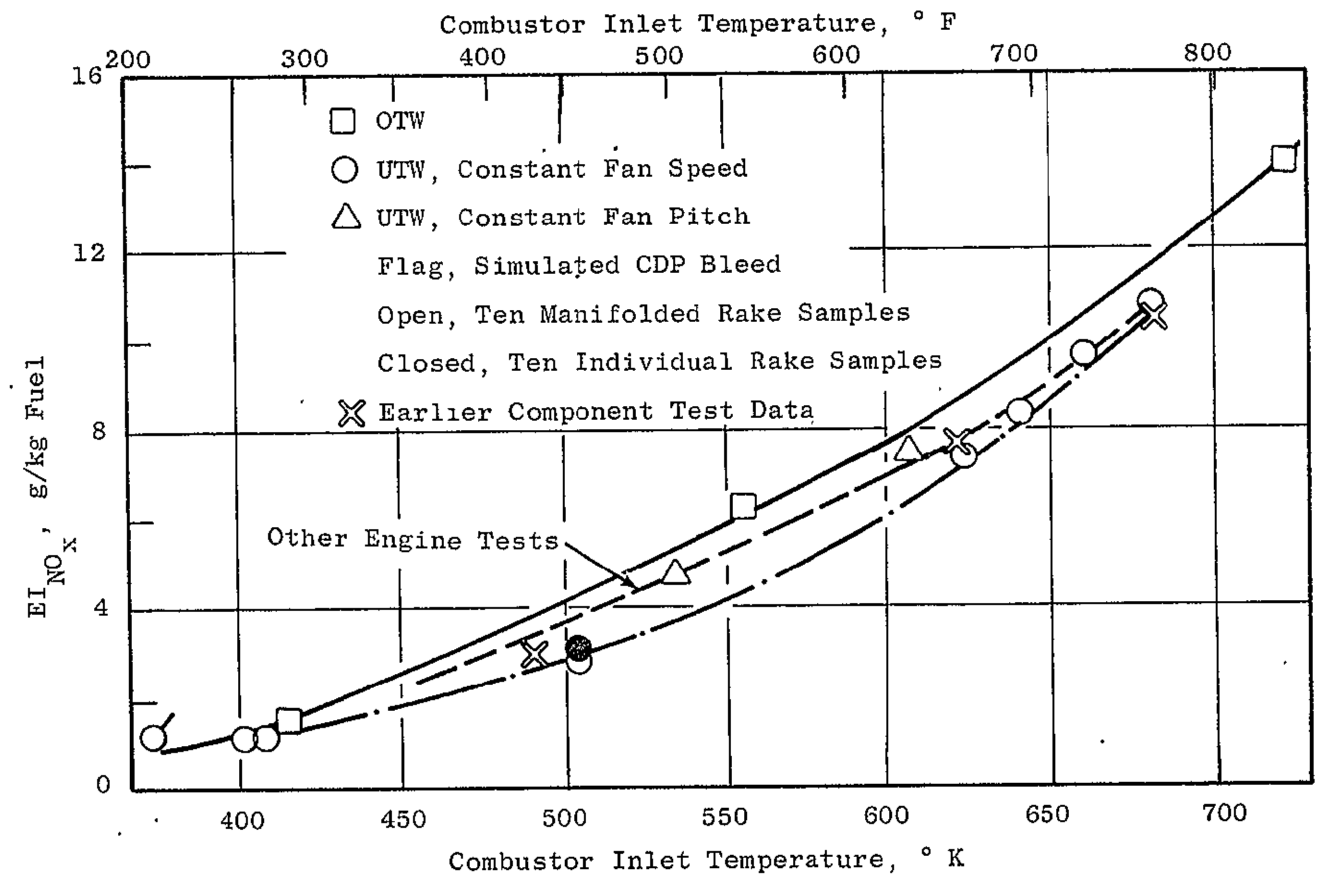

Figure 15. Under-the-Wing and Over-the-Wing NO_X Emissions Indices versus Combustor Inlet Temperature.

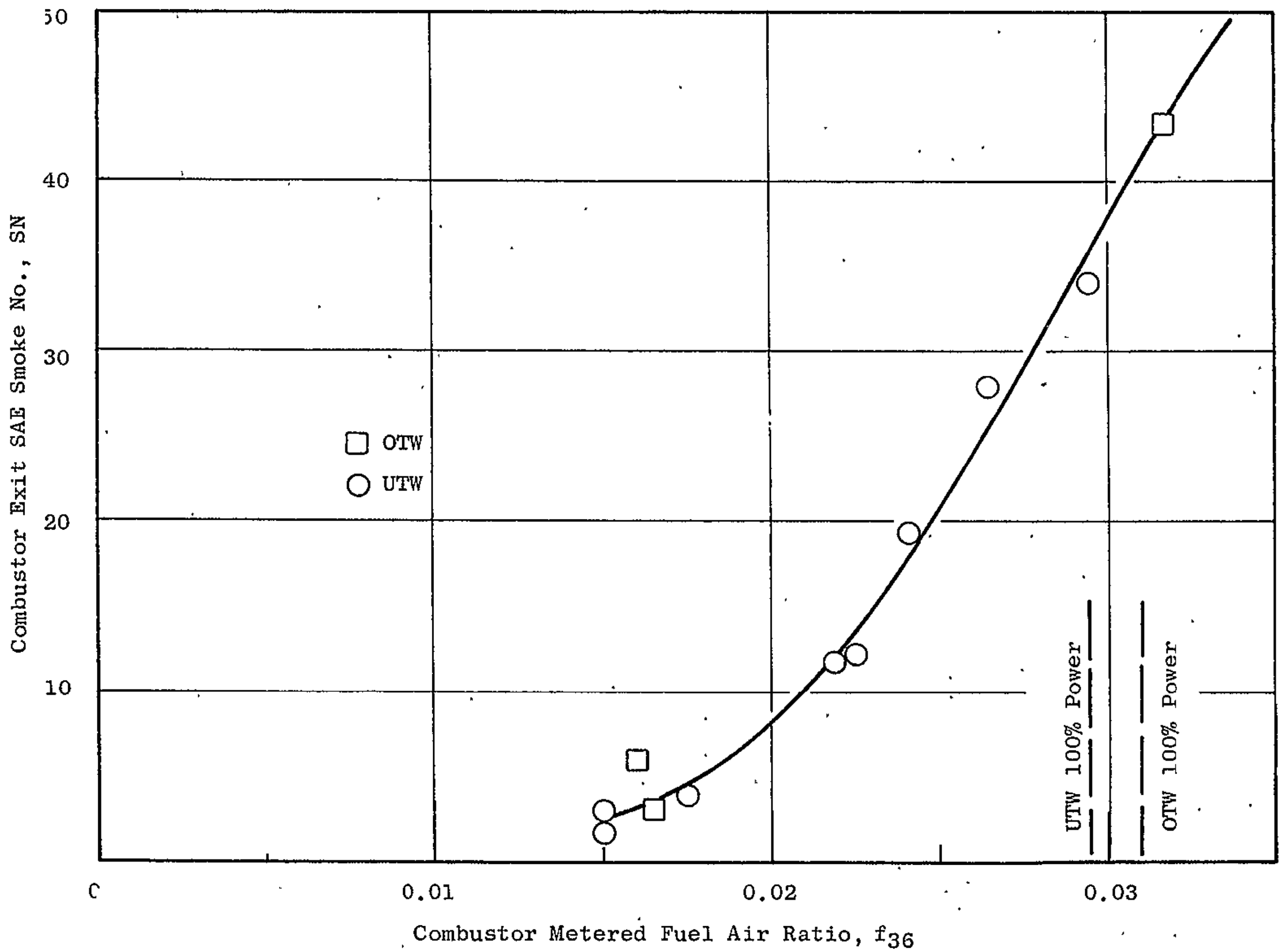

Figure 16. Combustor Exit Smoke Number versus Metered Fuel/Air Ratio.

Dome Equivalence Ratio Comparison at Takeoff Power

	Fuel/Air Ratio at Station 36	Equivalence Ratio-Dome	Percent Deviation from Design Value
F101	0.026	1.53	0
CFM56	0.025	1.47	-4
QCSEE-UTW	0.029	1.71	+12
QCSEE-OTW	0.031	1.83	+20

Because additional air is mixed with the combustor exhaust gases prior to the engine exhaust nozzle exit, the smoke particles are diluted at the measuring station downstream of the nozzle exit. In the case of the UTW, which has separated core and fan flows, only a small amount of turbine cooling air is introduced downstream of the combustor prior to the exhaust nozzle exit. This results in a smoke number about 12% lower than the number measured at the combustor exit, which would still be quite high. However, in the case of the OTW where the core stream is mixed with large quantities of fan air upstream of the exhaust nozzle exit, the resultant smoke numbers expected would be very low. For the OTW which has a bypass ratio (fan air/core air) of about 10 a reduction of about 80% would be expected if complete mixing of the two streams were obtained. The extimated smoke numbers of measuring stations immediately downstream of the UTW and OTW engine exhaust nozzles are plotted in Figure 17 versus T_3.

The gaseous emissions and smoke data for the UTW and OTW engines in terms of percent engine takeoff power are presented in Figures 18 and 19, respectively.

E. Application of QCSEE Combustor Emissions Data to the EPA Standards

To determine the status of a given combustor system or engine with regard to the applicable emissions category, it is necessary to perform calculations based on a prescribed EPA takeoff landing cycle (Table II) to obtain the emissions levels in terms of the EPA parameter. The results of these calculations are based on engine operating conditions and the appropriate emissions data at the specified EPA operating condition from the test results of the source under investigation.

Tables IX-XIV show details of the calculations of the EPA parameters for the QCSEE UTW and OTW engines based on engine performance from the most recent cycle deck at the EPA rating points and emissions data obtained in this test series. Emission indices at the specified cycle conditions were used unadjusted but the cycle fuel flow was adjusted to correspond to the combustion efficiency values determined from the emissions data. The data of Tables IX-XIV show that, based on the component emissions test data, the QCSEE UTW and OTW engines would meet the NO_x EPA Standard but requires significant reductions in CO and C_xH_y emissions to meet the applicable EPA Standards.

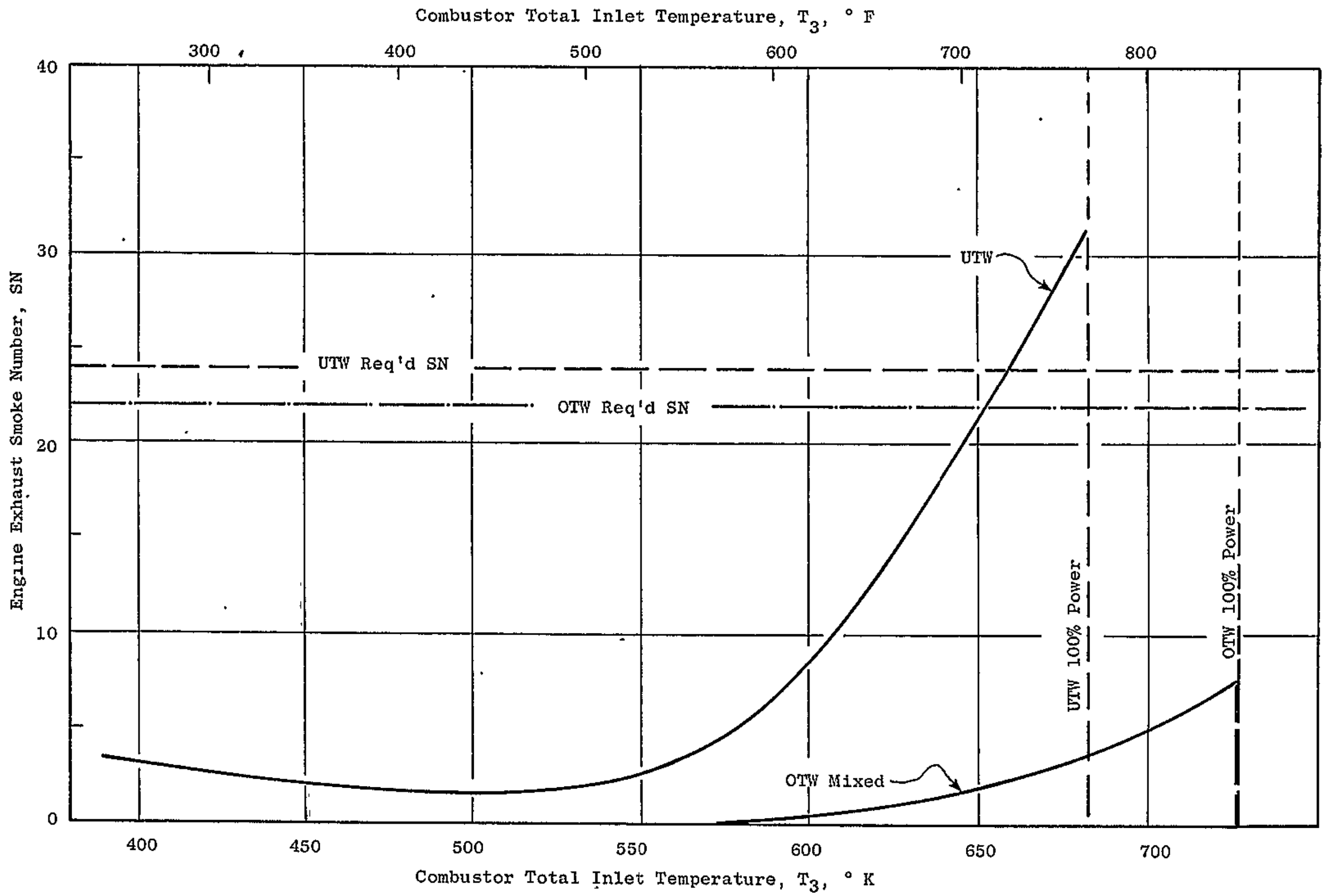

Figure 17. Engine Exhaust Smoke Number versus Combustor Inlet Temperature.

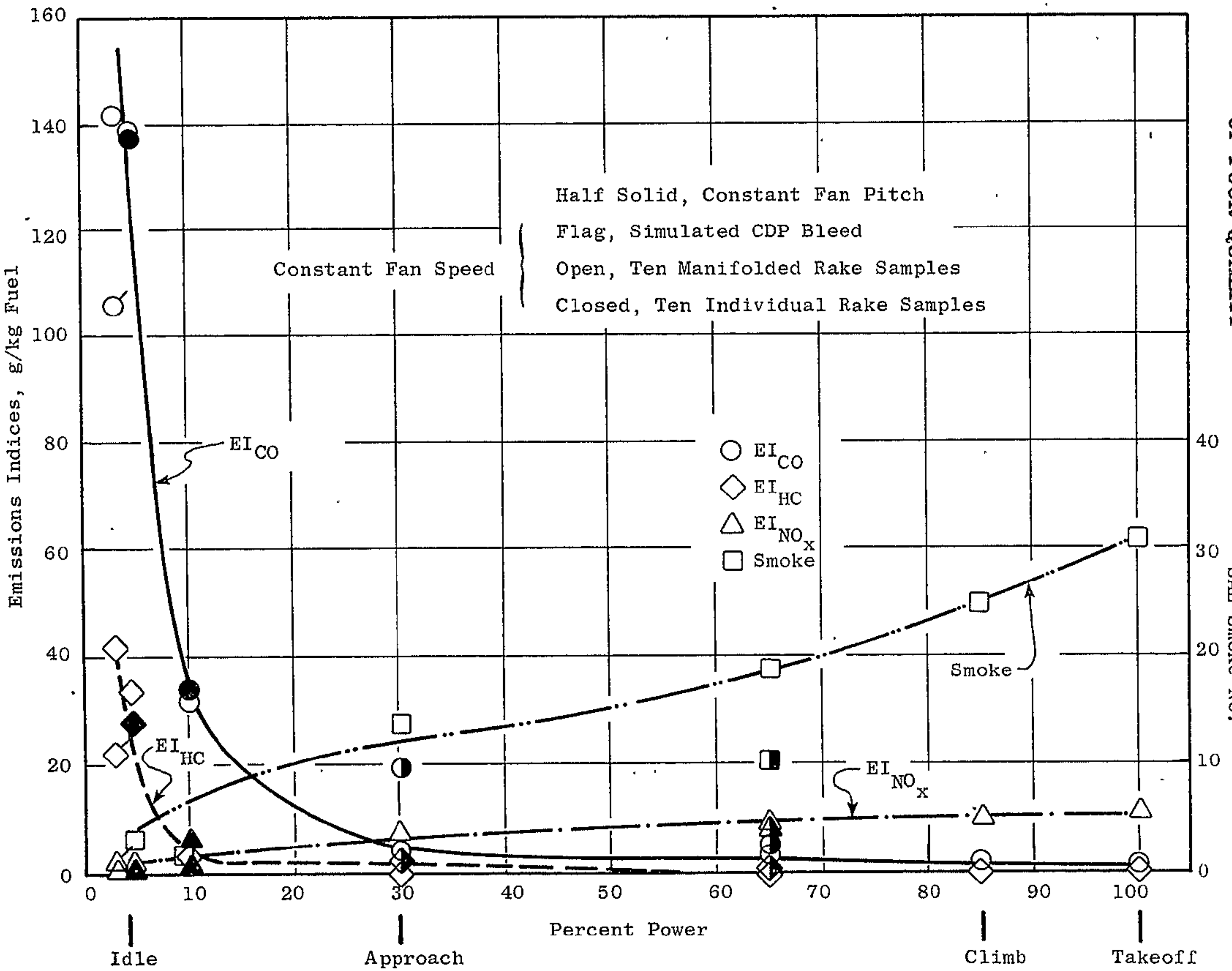

Figure 18. Under-the-Wing Engine Emissions versus Percent Power.

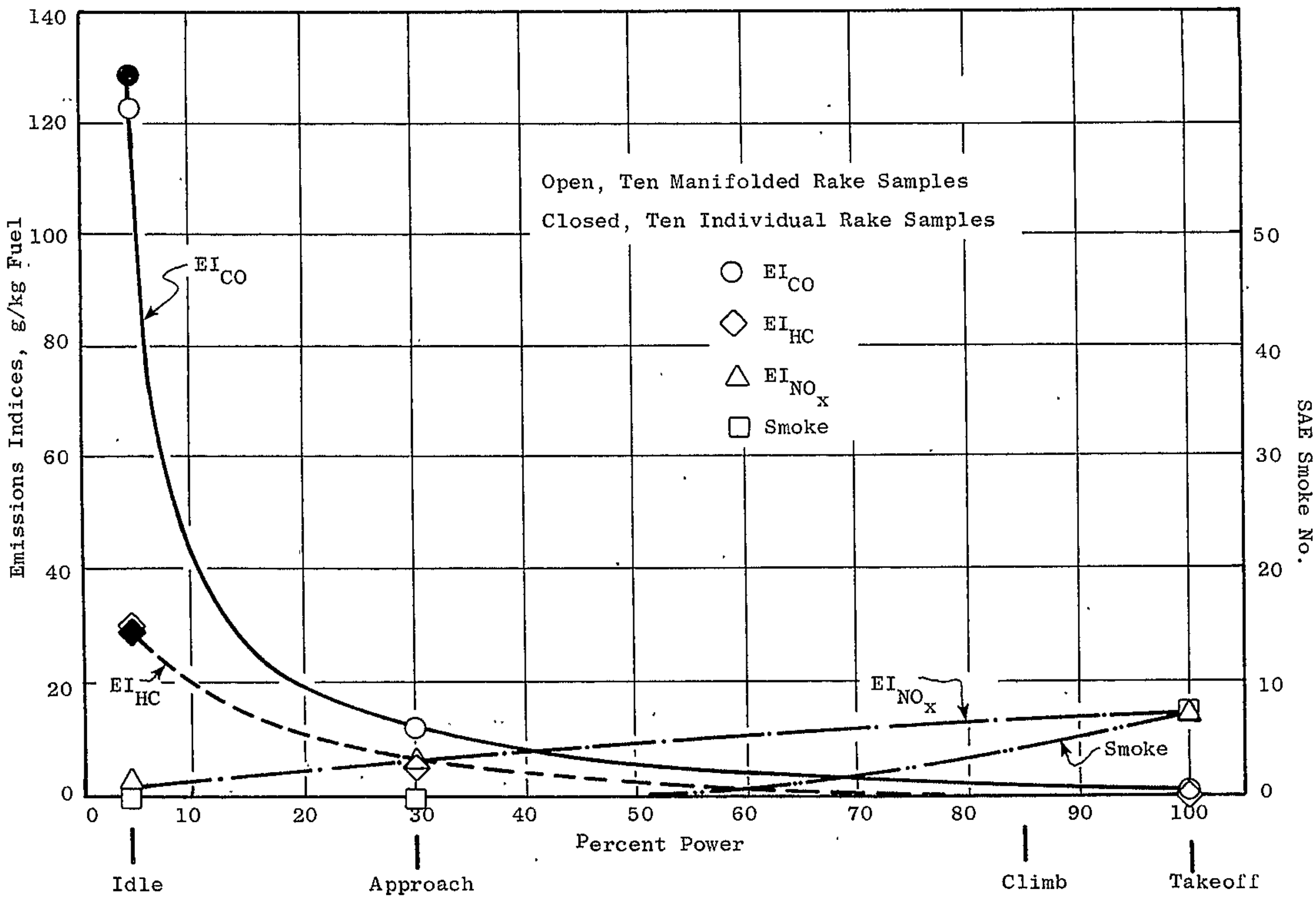

Figure 19. Over-the-Wing Engine Emissions versus Percent Power.

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Table IX. Emissions Calculations using Prescribed EPA Landing Cycle - UTW/CFP.

DATE - 6/75
ENGINE PERFORMANCE SOURCE - QCSEE UTW-4ENG-CFP
EMISSIONS DATA SOURCE - F101 PFRT(S/N47)-CELLA3-6/75
FUEL TYPE - JP5
ENGINE CLASS - T2

BASED ON COMPONENT TEST EMISSIONS CURVES

	********* EPA CYCLE CONDITION **********			
	IDLE	APPROACH	CLIMB	TAKEOFF
ENGINE PARAMETERS				
TIME (MINUTES).............	26.00	4.00	2.20	0.70
PERCENT POWER..............	4.50	30.00	85.00	100.00
THRUST (LBS)...............	783.	5221.	14792.	17402.
FUEL FLOW (PPH)............	674.	1601.	4467.	5580.
SFC (PPH/LB THRUST)........	0.8608	0.3067	0.3020	0.3207
THRUST-HOURS...............	339.30	348.04	542.36	203.02
EMISSIONS PARAMETERS				
CARBON MONOXIDE				
LB/1000 LB FUEL.........	129.000	21.000	2.100	1.500
LB/HOUR.................	86.946	33.621	9.381	8.370
LBS.....................	37.677	2.241	0.344	0.098
PCT. OF TOTAL LBS......	93.352	5.554	0.852	0.242
HYDROCARBONS				
LB/1000 LB FUEL.........	28.500	1.600	0.	0.
LB/HOUR.................	19.209	2.562	0.	0.
LBS.....................	8.324	0.171	0.	0.
PCT. OF TOTAL LBS......	97.990	2.010	0.	0.
OXIDES OF NITROGEN				
LB/1000 LB FUEL.........	1.200	4.600	9.000	10.800
LB/HOUR.................	0.809	7.365	40.203	60.264
LBS.....................	0.350	0.491	1.474	0.703
PCT. OF TOTAL LBS......	11.611	16.265	48.834	23.291

SUMMARY

	**************** EPA PARAMETER **************** (LB EMISSION/1000 LB THRUST-HR-CYCLE)		
	CALCULATED LEVEL	1979 STANDARD	PCT. REDUCTION REQUIRED
CARBON MONOXIDE....	28.17	4.30	84.74
HYDROCARBONS.......	5.93	0.80	86.51
OXIDES OF NITROGEN.	2.11	3.00	0.

Table X. Emissions Calculations using Prescribed EPA Landing Cycle - UTW/CFS.

DATE - 6/75
ENGINE PERFORMANCE SOURCE - QCSEE UTW-4ENG-CFS
EMISSIONS DATA SOURCE - F101 PFRT(S/N47)-CELLA3-6/75
FUEL TYPE - JP5
ENGINE CLASS - T2

BASED ON COMPONENT TEST EMISSIONS CURVES

	********* EPA CYCLE CONDITION *********			
	IDLE	APPROACH	CLIMB	TAKEOFF
ENGINE PARAMETERS				
TIME (MINUTES)............	26.00	4.00	2.20	0.70
PERCENT POWER.............	4.50	30.00	85.00	100.00
THRUST (LBS)..............	783.	5221.	14792.	17402.
FUEL FLOW (PPH)...........	674.	3320.	4775.	5580.
SFC (PPH/LB THRUST).......	0.8608	0.6359	0.3228	0.3207
THRUST-HOURS..............	339.30	348.04	542.36	203.02
EMISSIONS PARAMETERS				
CARBON MONOXIDE				
LB/1000 LB FUEL.........	129.000	4.000	2.000	1.500
LB/HOUR.................	86.946	13.280	9.550	8.370
LBS.....................	37.677	0.885	0.350	0.098
PCT. OF TOTAL LBS.......	96.583	2.270	0.898	0.250
HYDROCARBONS				
LB/1000 LB FUEL.........	28.500	0.200	0.	0.
LB/HOUR.................	19.209	0.664	0.	0.
LBS.....................	8.324	0.044	0.	0.
PCT. OF TOTAL LBS.......	99.471	0.529	0.	0.
OXIDES OF NITROGEN				
LB/1000 LB FUEL.........	1.200	7.200	9.300	10.800
LB/HOUR.................	0.809	23.904	44.407	60.264
LBS.....................	0.350	1.594	1.628	0.703
PCT. OF TOTAL LBS.......	8.198	37.273	38.084	16.445

SUMMARY

	*************** EPA PARAMETER *************** (LB EMISSION/1000 LB THRUST-HR-CYCLE)		
	CALCULATED LEVEL	1979 STANDARD	PCT. REDUCTION REQUIRED
CARBON MONOXIDE....	27.23	4.30	84.21
HYDROCARBONS.......	5.84	0.80	86.30
OXIDES OF NITROGEN.	2.98	3.00	0.

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Table XI. Emissions Calculations using Prescribed EPA Landing Cycle - OTW.

DATE - 6/75
ENGINE PERFORMANCE SOURCE - QCSEE OTW-4ENG
EMISSIONS DATA SOURCE - F101 PFRT(S/N47)-CELLA3-6/75
FUEL TYPE - JP5
ENGINE CLASS - T2

BASED ON COMPONENT TEST EMISSIONS CURVES

	********* EPA CYCLE CONDITION **********			
	IDLE	APPROACH	CLIMB	TAKEOFF
ENGINE PARAMETERS				
TIME (MINUTES).............	26.00	4.00	2.20	0.70
PERCENT POWER.............	4.50	30.00	85.00	100.00
THRUST (LBS)..............	913.	6090.	17255.	20300.
FUEL FLOW (PPH)...........	665.	1884.	5501.	6881.
SFC (PPH/LB THRUST).......	0.7284	0.3094	0.3188	0.3390
THRUST-HOURS..............	395.63	406.00	632.68	236.83
EMISSIONS PARAMETERS				
CARBON MONOXIDE				
LB/1000 LB FUEL.........	126.000	13.000	2.100	1.000
LB/HOUR.................	83.790	24.492	11.552	6.881
LBS.....................	36.309	1.633	0.424	0.080
PCT. OF TOTAL LBS......	94.442	4.247	1.102	0.209
HYDROCARBONS				
LB/1000 LB FUEL.........	30.000	1.000	0.300	0.
LB/HOUR.................	19.950	1.884	1.650	0.
LBS.....................	8.645	0.126	0.061	0.
PCT. OF TOTAL LBS......	97.893	1.422	0.685	0.
OXIDES OF NITROGEN				
LB/1000 LB FUEL.........	1.600	6.000	11.900	14.200
LB/HOUR.................	1.064	11.304	65.462	97.710
LBS.....................	0.461	0.754	2.400	1.140
PCT. OF TOTAL LBS......	9.697	15.849	50.480	23.974

SUMMARY

**************** EPA PARAMETER ****************
(LB EMISSION/1000 LB THRUST-HR-CYCLE)

	CALCULATED LEVEL	1979 STANDARD	PCT. REDUCTION REQUIRED
CARBON MONOXIDE....	23.01	4.30	81.31
HYDROCARBONS.......	5.28	0.80	84.86
OXIDES OF NITROGEN.	2.85	3.00	0.

Table XII. Emissions Calculation using Prescribed EPA Landing Cycle - UTW/CFP (Sector Burn).

DATE - 6/75
ENGINE PERFORMANCE SOURCE - QCSEE UTW-4ENG-CFP(SECTOR BURN 10 CUP)
EMISSIONS DATA SOURCE - F101 PFRT(S/N47)-CELLA3-6/75
FUEL TYPE - JP5
ENGINE CLASS - T2

BASED ON COMPONENT TEST EMISSIONS CURVES

	********* EPA CYCLE	CONDITION	**********	
	IDLE	APPROACH	CLIMB	TAKEOFF
ENGINE PARAMETERS				
TIME (MINUTES).............	26.00	4.00	2.20	0.70
PERCENT POWER..............	4.50	30.00	85.00	100.00
THRUST (LBS)...............	783.	5221.	14792.	17402.
FUEL FLOW (PPH)............	646.	1601.	4467.	5580.
SFC (PPH/LB THRUST)........	0.8250	0.3067	0.3020	0.3207
THRUST-HOURS...............	339.30	348.04	542.36	203.02
EMISSIONS PARAMETERS				
CARBON MONOXIDE				
LB/1000 LB FUEL.........	80.000	21.000	2.100	1.500
LB/HOUR.................	51.680	33.621	9.381	8.370
LBS.....................	22.395	2.241	0.344	0.098
PCT. OF TOTAL LBS......	89.301	8.938	1.372	0.389
HYDROCARBONS				
LB/1000 LB FUEL.........	6.000	1.600	0.	0.
LB/HOUR.................	3.876	2.562	0.	0.
LBS.....................	1.680	0.171	0.	0.
PCT. OF TOTAL LBS......	90.771	9.229	0.	0.
OXIDES OF NITROGEN				
LB/1000 LB FUEL.........	1.200	4.600	9.000	10.800
LB/HOUR.................	0.775	7.365	40.203	60.264
LBS.....................	0.336	0.491	1.474	0.703
PCT. OF TOTAL LBS......	11.182	16.344	49.070	23.404

SUMMARY

	**************** EPA PARAMETER **************** (LB EMISSION/1000 LB THRUST-HR-CYCLE)		
	CALCULATED LEVEL	1979 STANDARD	PCT. REDUCTION REQUIRED
CARBON MONOXIDE....	17.50	4.30	75.43
HYDROCARBONS.......	1.29	0.80	38.06
OXIDES OF NITROGEN.	2.10	3.00	0.

Table XIII. Emissions Calculations using Prescribed EPA Landing Cycle - UTW/CFS (Sector Burn).

DATE - 6/75
ENGINE PERFORMANCE SOURCE - QCSEE UTW-4ENG-CFS(SECTOR BURN 10 CUP)
EMISSIONS DATA SOURCE - F101 PFRT(S/N47)-CELLA3-6/75
FUEL TYPE - JP5
ENGINE CLASS - T2

BASED ON COMPONENT TEST EMISSIONS CURVES

	********* EPA CYCLE CONDITION **********			
	IDLE	APPROACH	CLIMB	TAKEOFF
ENGINE PARAMETERS				
TIME (MINUTES)............	26.00	4.00	2.20	0.70
PERCENT POWER.............	4.50	30.00	85.00	100.00
THRUST (LBS)..............	783.	5221.	14792.	17402.
FUEL FLOW (PPH)...........	646.	3320.	4775.	5580.
SFC (PPH/LB THRUST).......	0.8250	0.6359	0.3228	0.3207
THRUST-HOURS..............	339.30	348.04	542.36	203.02
EMISSIONS PARAMETERS				
CARBON MONOXIDE				
LB/1000 LB FUEL........	80.000	4.000	2.000	1.500
LB/HOUR................	51.680	13.280	9.550	8.370
LBS....................	22.395	0.885	0.350	0.098
PCT. OF TOTAL LBS......	94.381	3.731	1.476	0.412
HYDROCARBONS				
LB/1000 LB FUEL........	6.000	0.200	0.	0.
LB/HOUR................	3.876	0.664	0.	0.
LBS....................	1.680	0.044	0.	0.
PCT. OF TOTAL LBS......	97.432	2.568	0.	0.
OXIDES OF NITROGEN				
LB/1000 LB FUEL........	1.200	7.200	9.300	10.800
LB/HOUR................	0.775	23.904	44.407	60.264
LBS....................	0.336	1.594	1.628	0.703
PCT. OF TOTAL LBS......	7.884	37.401	38.215	16.501

SUMMARY

**************** EPA PARAMETER ****************
(LB EMISSION/1000 LB THRUST-HR-CYCLE)

	CALCULATED LEVEL	1979 STANDARD	PCT. REDUCTION REQUIRED
CARBON MONOXIDE....	16.56	4.30	74.04
HYDROCARBONS.......	1.20	0.80	33.51
OXIDES OF NITROGEN.	2.97	3.00	0.

Table XIV. Emissions Calculations using Prescribed EPA Landing Cycle - OTW (Sector Burn).

DATE - 6/75
ENGINE PERFORMANCE SOURCE - QCSEE OTW-4ENG-10 CUP SECTOR BURN
EMISSIONS DATA SOURCE - F101 PFRT(S/N47)-CELLA3-6/75
FUEL TYPE - JP5
ENGINE CLASS - T2

BASED ON COMPONENT TEST EMISSIONS CURVES

	********* EPA CYCLE	CONDITION	*********	
	IDLE	APPROACH	CLIMB	TAKEOFF
ENGINE PARAMETERS				
TIME (MINUTES).............	26.00	4.00	2.20	0.70
PERCENT POWER..............	4.50	30.00	85.00	100.00
THRUST (LBS)...............	913.	6090.	17255.	20300.
FUEL FLOW (PPH)............	638.	1884.	5501.	6881.
SFC (PPH/LB THRUST)........	0.6988	0.3094	0.3188	0.3390
THRUST-HOURS...............	395.63	406.00	632.68	236.83
EMISSIONS PARAMETERS				
CARBON MONOXIDE				
LB/1000 LB FUEL.........	60.000	13.000	2.100	1.000
LB/HOUR.................	38.280	24.492	11.552	6.881
LBS.....................	16.588	1.633	0.424	0.080
PCT. OF TOTAL LBS......	88.589	8.720	2.262	0.429
HYDROCARBONS				
LB/1000 LB FUEL.........	5.000	1.000	0.300	0.
LB/HOUR.................	3.190	1.884	1.650	0.
LBS.....................	1.382	0.126	0.061	0.
PCT. OF TOTAL LBS......	88.134	8.008	3.858	0.
OXIDES OF NITROGEN				
LB/1000 LB FUEL.........	1.600	6.000	11.900	14.200
LB/HOUR.................	1.021	11.304	65.462	97.710
LBS.....................	0.442	0.754	2.400	1.140
PCT. OF TOTAL LBS......	9.340	15.912	50.680	24.069

SUMMARY

**************** EPA PARAMETER ****************
(LB EMISSION/1000 LB THRUST-HR-CYCLE)

	CALCULATED LEVEL	1979 STANDARD	PCT. REDUCTION REQUIRED
CARBON MONOXIDE....	11.20	4.30	61.62
HYDROCARBONS.......	0.94	0.80	14.76
OXIDES OF NITROGEN.	2.83	3.00	0.

With sector burning, the local combustor fuel/air ratio is increased, providing more favorable combustion zone stoichiometry at idle, which results in lower emissions of CO and C_xH_y as shown eariler in Figure 11. Tables IX-XI show that reductions in the EPA parameter for CO and C_xH_y are obtained when only ten of the 20 injectors are fueled. In this instance, the component data were used directly for the UTW application and the sector burning idle emissions levels were estimated for the OTW case. Even with the large reductions in CO and C_xH_y emissions demonstrated with sector burning at idle, the resulting EPA parameters for CO and C_xH_y emissions are still above the applicable standards. A summary of the QCSEE component test emissions results for the UTW and OTW engine is shown in Table XV in terms of the EPA parameter. To meet the applicable CO and C_xH_y emissions standards, as defined by the EPA, emissions indices at ground idle operating conditions of about 20 and 4 g/kg of fuel, respectively, are required for the UTW and OTW engines.

The applicable EPA smoke standards for the UTW and OTW are 24 and 22, respectively, and become effective January 1, 1979. Based on the component test results and the core and fan air flows of the two QCSEE engines, the OTW (mixed core and fan flow) engine would have a smoke number less than 10 and would meet the EPA Standards whereas, the UTW (unmixed core flow) would have a smoke number greater than 24, the applicable EPA Standard for the UTW engine.

F. Combustor Performance Results

A very limited amount of combustor performance data was obtained on the QCSEE combustor since this combustor design has already accumulated a significant amount of test experience over a wide range of operating conditions in other engine applications. Since performance data is available for operating conditions comparable to the QCSEE UTW and OTW engines only those parameters considered necessary for monitoring combustor operating limits and emission gas sampling were measured.

1. Pressure Drop Results

Overall pressure drop was measured throughout the test by total pressure probes located upstream of the outlet guide vanes and at the combustor exit. The calculated pressure drop (P_{T3} - $P_{T3.9}/P_{T3}$) is shown versus flow function $(W_c/P_3)^2$ T_3 for several combustor conditions in Figure 20 with the UTW and OTW design pressure drops shown for reference. The combustor dome pressure drop was also measured during the test and is shown also in Figure 20. This combustor instrumentation will remain intact for engine testing.

2. Liner Skin Temperature Test Results

A total of five outer-liner and five inner-liner skin thermocouples were employed to monitor liner skin temperature during the test. The maximum metal temperatures measured for UTW and OTW takeoff conditions are tabulated below:

Table XV. Summary of QCSEE Component Test Results Compared to the EPA Standards.

EPA Parameter; lb per 1000 lb Thrust - Hr/Cycle

		Constant Fan Pitch		Constant Fan Speed		
		Full Burning	With Sector Burning	Full Burning	With Sector Burning	EPA Requirement
UTW	CO	28.2	17.5	27.2	16.6	4.3
	C_xH_y	5.9	1.3	5.8	1.2	0.8
	NO_x	2.1	2.1	3.0	3.0	3.0
	Smoke	31		31		24
OTW	CO	23.0	11.2			4.3
	C_xH_y	5.3	0.9			0.8
	NO_x	2.8	2.8			3.0
	Smoke	7				22

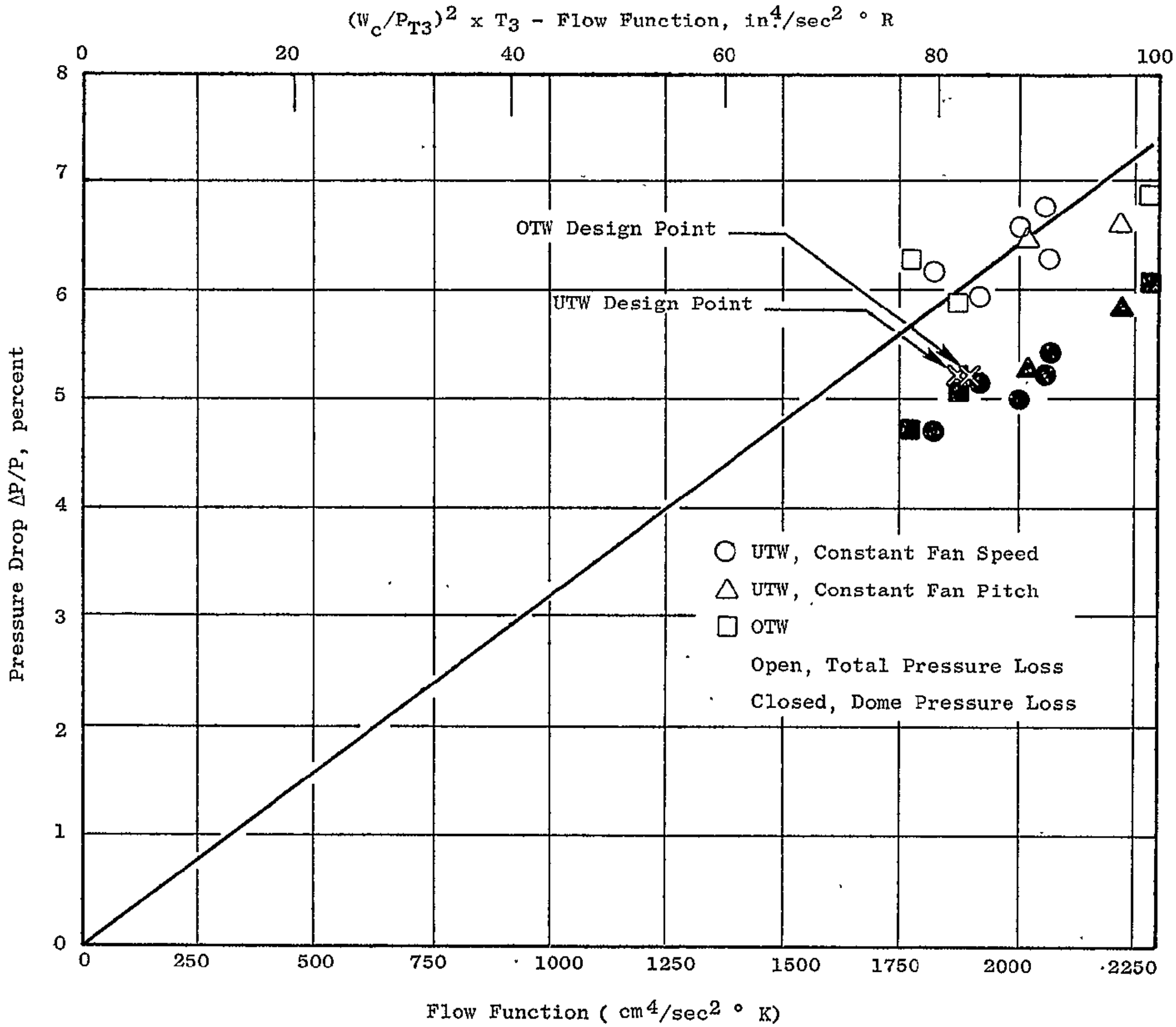

Figure 20. Combustor Pressure Drop versus Flow Function.

	Outer Liner	Inner Liner
UTW	Panel 3 - 956° K (1260° F)	Panel 2 - 952° K (1254° F)
OTW	Panel 3 - 1032° K (1398° F)	Panel 2 - 1012° K (1362° F)

The location of the combustor panels were shown in Figure 1.

3. Exit Profile Test Results

Radial profiles were measured at the UTW and OTW takeoff condition during the test by recording individual gas samples from rakes located between and in-line with swirl cups (Gas Sampling Mode IV). The sample fuel/air profiles recorded for the UTW and OTW takeoff conditions are shown in Figure 21.

4. Overall Performance of Exhaust Gas Sampling and Fuel System Supply System

Comparisons of the sampled to metered fuel/air ratios are illustrated in Figure 22. Good agreement between these two independently measured parameters was obtained, providing evidence that gas samples were representative. In combustor tests, the fuel/air ratios measured by gas sampling should always exceed the metered values because the gas samples are extracted only from the fueled portions of the combustor exit flow. Samples of the cooling air at the inner and outer boundaries of this flow are not usually obtained as part of the total sample. Good agreement between measured fuel system pressure drop and calibration fuel system pressure drop, as shown in Figure 23, provides assurance that the fuel system was operating satisfactorily.

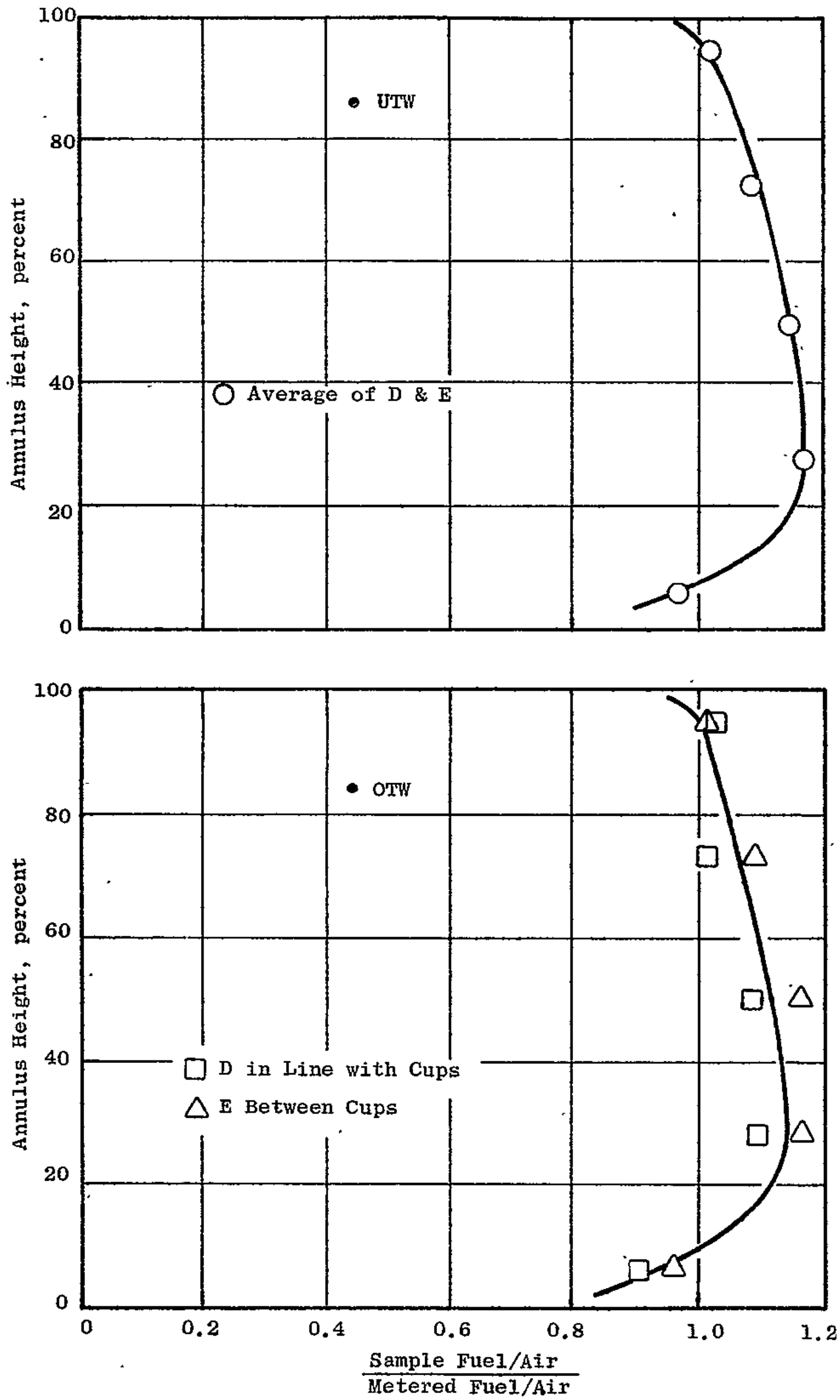

Figure 21. Under-the-Wing and Over-the-Wing Fuel/Air Radial Profile at Takeoff.

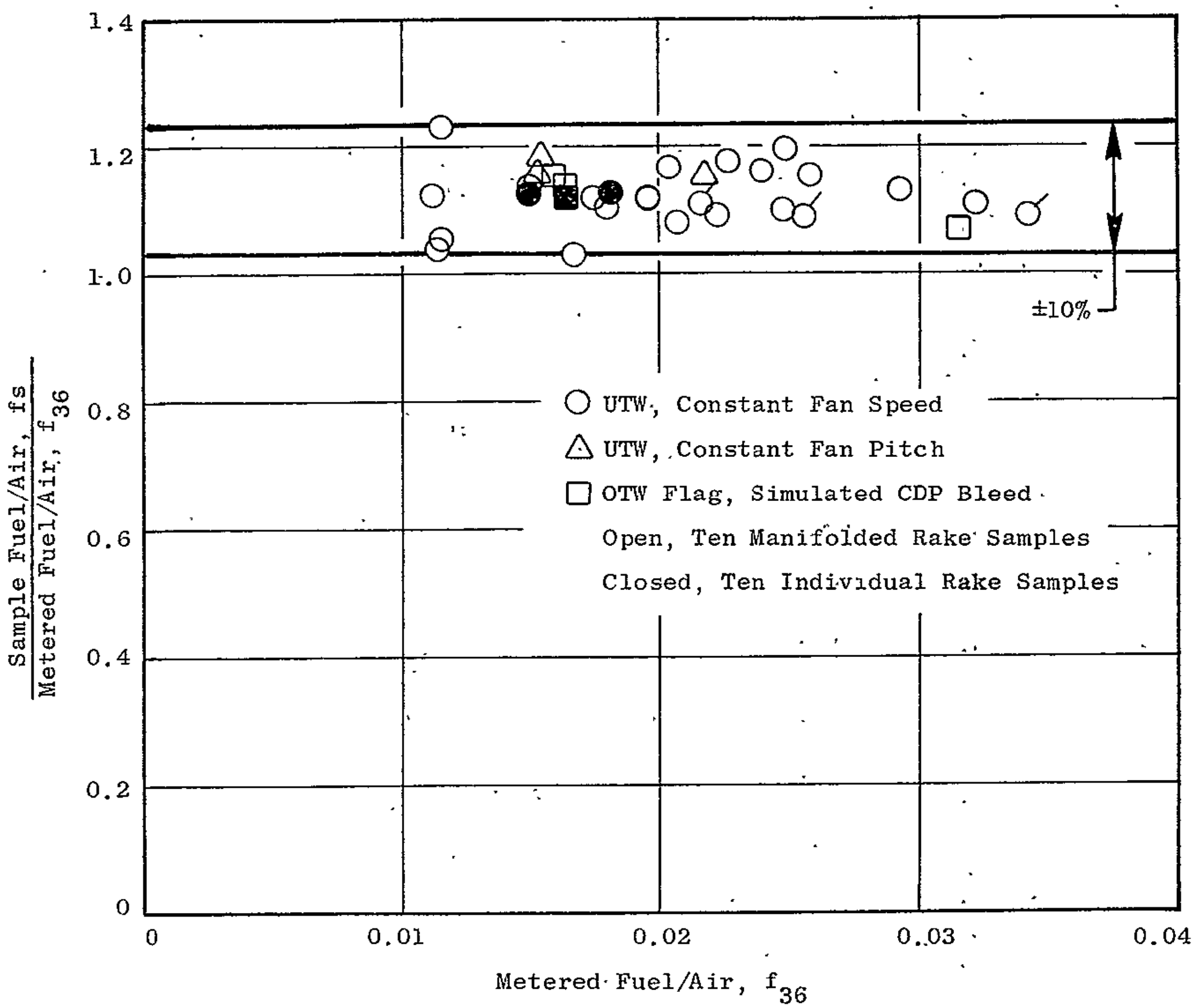

Figure 22. Sample Fuel/Air versus Metered Fuel/Air.

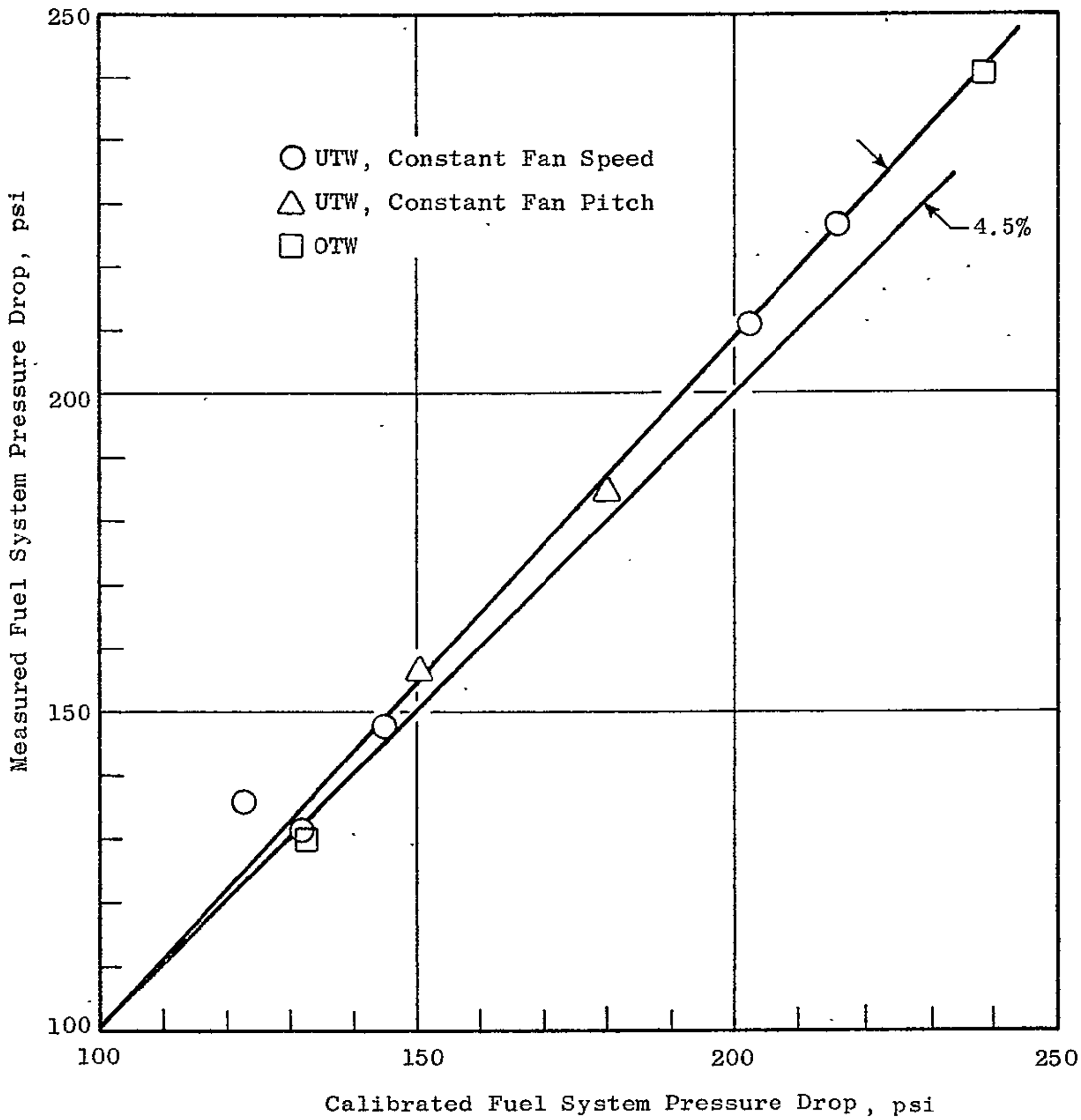

Figure 23. Comparison of Calibrated and Measured Fuel System Performance.

SECTION VIII

CONCLUSIONS

The measured gaseous emissions of the F101 PFRT combustor, when tested at the QCSEE UTW and OTW engines operating conditions, compared favorably with the emissions data from other component tests of this combustor. However, the measured CO and C_xH_y emissions levels at idle were higher than engine test data at similar conditions. This consistent discrepancy appears to be associated with leakage air bypassing the combustor, resulting in combustor fuel/air ratios higher than the value predicted in the engine cycle deck. If these higher combustor fuel/air ratios do exist in the engine, somewhat lower CO and C_xH_y levels would result creating the discrepancy between the test rig and engine emissions data.

The idle emissions measured for this PFRT F101 combustor at the UTW and OTW operating conditions result in EPA calculated levels which exceed the 1979 standards. Ten-cup sector burning provided significant reductions in CO and C_xH_y emissions indices, on the order of 40 and 80%, respectively; however, these reductions are still not sufficient to meet the applicable EPA Standards.

Because of the low combustor inlet temperatures at takeoff associated with low pressure ratio, high bypass ratio engines such as QCSEE, the NO_x emissions levels satisfy the applicable EPA Standards for both the UTW and OTW engines.

Disappointingly high smoke levels were obtained at takeoff operating conditions. With these high smoke levels, smoke visibility problems would be expected in the case of the UTW. These unusually high levels are attributed to design point fuel/air ratios for the QCSEE engines that are considerably higher than those of other F101 derivative engines.

SECTION IX

CONCLUDING REMARKS

In order to meet the C_xH_y and CO pollution goals, additional work is under consideration to develop a new Double-Annular Dome combustor for QCSEE. This combustor design would be derived from the best NASA Double-Annular Dome CF6-50 combustor which is being evolved in the NASA/GE Clean Combustor program. This combustor development will be conducted in a sector test rig and will concentrate on reducing idle emissions to meet the program goals.

SECTION X

NOMENCLATURE

Symbol	Quantity	Unit
CFP	Constant fan-pitch cycle	-
CPS	Constant fan-speed cycle	-
EI_x	Emission index of constituent x (x = CO, HC or NO_x)	g of x/kg fuel
f	Fuel/air ratio, fuel flow rate/airflow rate	-
f_m	Metered fuel/air ratio	-
f_s	Sample fuel/air ratio	-
f_{36}	Fuel/air ratio at the combustor exit plane	-
H	Inlet air humidity	g water/kg air
n	Fuel hydrogen-to-carbon atom ratio	-
P_{T_3}	Total pressure at the combustor inlet	N/m^2 (atm)
$P_{T3.9}$	Total pressure at the combustor exit	N/m^2 (atm)
ΔP_T	Total combustor pressure drop	N/m^2 (atm)
T_{T_3}	Total temperature at the combustor inlet	° K
W_c	Combustor airflow rate	kg/sec
W_3	Compressor exit airflow rate	kg/sec
W_f	Total fuel flow rate	kg/hr
η_o	Overall combustion efficiency	-

SECTION XI

REFERENCES

1. "Procedure for the Continuous Sampling and Measurment of Gaseous Emissions from Aircraft Turbine Engine," SAE Aerospace Recommended Practice 1256, October 1971.

2. "Aircraft Gas Turbine Engine Exhaust Smoke Measurement," SAE Aerospace Recommended Practice 1179, May 1970.

3. NASACAR 134737, "Experimental Clean Combustor Program - Phase I Final Report," Appendix B, DW Bahr, CC Gleason, June 1975.

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